Multisensory and sensorimotor origins of the sense of self

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Résumé

Les neurosciences cognitives sont de plus en plus intéressées par l'étude du sujet (c'est-à-dire, du soi) de l'expérience consciente. Afin d'être le sujet d'une expérience, il faut sentir que l'on possède un corps physique, qu'on est localisé dans ce corps, et pouvoir distinguer son corps et ses actions des corps et des actions des autres. Ces expériences pre-réflexives sont basées sur des mécanismes cérébraux de l'intégration multisensorielle et sensorimotrice. Dans cette thèse, j'ai étudié comment notre sens de soi, et en particulier, les sentiments d'avoir un corps et d'être l'agent de ses actions (sentiment d'agentivité), dépendent de signaux corporels multimodaux. J'ai atteint cet objectif en utilisant des approches développées par les neurosciences cognitives pour étudier le sens de soi corporel: à travers la création des illusions corporelles avec des conflits multisensoriels grâce à l'utilisation de la réalité virtuelle et la technologie robotique. La première partie de cette thèse décrit l'investigation du sentiment d'avoir un corps chez les sujets sains et chez les patients avec la lésion de la moelle épinière, à travers l'induction des conflits entre l'information tactile et visuelle. La recherche présentée dans la deuxième partie de la thèse est centrée sur l'expérience du toucher auto-dirigé. Là, j'ai d'abord étudié comment la manipulation de cadres de référence visuo-spatiaux influence l'illusion du toucher auto-dirigé et ensuite, comment le toucher actif influence le sentiment d'avoir un corps. Enfin, dans la troisième partie de la thèse, j'ai étudié comment les conflits multisensoriels et sensorimoteurs perturbent le sentiment de soi chez des sujets sains et induisent des expériences similaires à certains symptômes observés dans les troubles neurologiques et psychiatriques. Je montre que les conflits entre certains signaux corporels influencent non seulement la perception du corps et le sentiment d'agentivité pour les actions motrices mais aussi se propagent à des niveaux plus élevés et influencent même le sens de l'agentivité pour les représentations mentales chez des sujets sains. Pour conclure, je discute mes résultats et leur relation avec les connaissances existantes sur la conscience de soi corporelle et je les positionne dans le cadre plus grand de notre compréhension actuelle du soi.

Mots-clés: appartenance du corps, agentivité, sensorimoteur, intégration multisensorielle, soi, insertion de pensée, lésions de la moelle épinière

Abstract

Cognitive neuroscience has increasingly focused on studying the subject, i.e. the self, of conscious experience. In order to be the subject of an experience, we generally experience owning a physical body, being located within that body, and being able to distinguish the body and its actions from others. These pre-reflective experiences are based on brain mechanisms of multisensory and sensorimotor integration. In this thesis I investigated how our sense of self, in particular the senses of body ownership and of agency, depend on multimodal bodily signals. I achieved this by using approaches developed by cognitive neuroscience to study how the sense of self relates to the processing of bodily signals: creating bodily illusions with multisensory conflicts through the use of virtual reality and robotics. The first part of this thesis describes the investigation of the sense of body ownership in healthy subjects and in spinal cord injury patients, achieved by inducing conflicts between tactile information and visual feedback. The research presented in the second part of the thesis is centered on the experience of self-touch. There, I have first investigated how the manipulation of reference frames influences the perception of the illusion of self-touch, and second, how active self-touch influences the sense of body ownership. Lastly, in the third part of the thesis, I investigated how experimentally induced multisensory and sensorimotor conflicts perturb the sense of self in healthy subjects and induce experiences similar to certain symptoms observed in neurological and psychiatric disorders. I show that particular conflicts between bodily signals not only affect body perception and sense of agency for motor actions but also propagate to higher levels and influence even the sense of agency for mental representations in healthy subjects. Finally, I discuss my results and their relation to existing knowledge on bodily self-consciousness and position them in a broader picture of our current understanding of the self.

Key words: body ownership, agency, sensorimotor, multisensory integration, self, thought insertion, spinal cord injury

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“The human body is an object and a subject, the outside of an inside that cannot be seen. The human body lives in the mind of one who possesses a human body, and to live inside the human body possessed of the mind that perceives another human body is to live in a world of others.”

Paul Auster (Sunset Park)

1 INTRODUCTION

“Who am I? Who is this person in the mirror? Is this my hand hitting the keyboard? Was it me who moved my hand to type these words? Is it me who is thinking these thoughts?” The sense of self is an important human feature, giving us a sense of identity, unity, and continuity. It enables us to distinguish ourselves from others and to relate to the world that surrounds us. While the self as the object (“me”) might be often in the focus of our awareness, this is less the case for the self as subject, and we usually do not doubt that we are the subjects, the “I” of our conscious experience. Understanding what is the sense of self, and how it is constructed, is not only important for the comprehension of who are we, but it also promises to advance our understanding of many clinical conditions where the sense of self is compromised, as for in example autoscopic hallucinations, or in schizophrenia.

The several aspects of the sense of self have been the subjects of inquiry for centuries in multiple disciplines, including philosophy, sociology, psychology and neuroscience. Consequently, many notions, definitions, and concepts of self have been established (Gallagher, 2000; Zahavi, 2005). Broadly, these approaches can be divided into two groups that focus on different aspects of the self: the *narrative (or cognitive) self,* and the *minimal self* (Gallagher, 2000).

The approach of the *narrative self* studies the self as an entity extended in time and depending on explicit cognition and language (Blanke & Metzinger, 2009; Gallagher, 2000; Zahavi, 2005), and has been oriented to higher-level aspects of the sense of self, for example autobiographic memory, personality, language, or social identity.

On the other hand, increasing interest has mounted the study of the minimal self, or the pre-reflective form of self-consciousness. This is the immediate awareness of being a subject of experience, grounded in the bodily foundations of self-consciousness (Blanke & Metzinger, 2009; Gallagher, 2000). This approach investigates the self by studying how we perceive our body and targets the brain mechanisms that process bodily information, i.e. bodily self-consciousness (Berlucchi & Aglioti, 1997; Blanke & Metzinger, 2009; Blanke, 2012; Damasio, 2000; Gallagher, 2000; Zahavi, 2005)

In line with this approach, the research presented in this thesis aims to elucidate how the sense of self is linked to our body and how it depends on the body-related sensory information processed by our brain. This has been achieved by manipulating motor signals and body-related sensory information (vision, touch, and proprioception) through manual or automatized stimulation using the techniques of virtual reality and robotics.

In the subsequent chapters of the introduction I describe in more detail the theoretical background of bodily-self consciousness and delineate its principal components. I provide a brief overview of existing theories and research in neuroscience that have stemmed from this perspective and are relevant for my own research. At the end of the introduction I will outline the principal findings of my doctoral research, which are then in details presented in the next section. Finally, I will discuss these findings and position them in a broader picture of our current understanding of the self.

1.1 BODILY SELF-CONSCIOUSNESS

Bodily self-consciousness is defined as the pre-reflective, immediate awareness to be the subject, the “I” of experience, to reside in a body, and to have a control over that body (Blanke & Metzinger, 2009; Blanke, 2012). The experimental research has been focused on studying its principal components: the **embodiment** and the **sense of agency** (Blanke & Metzinger, 2009; Gallagher, 2000). The fundamental aspects of embodiment are the sense of owning a body and self-identification with that body (*body ownership*), the sense of being located within the physical boundaries of that body (*self-location*) and perception of the world from the visuo-spatial perspective of that body (*first person perspective*) (Blanke & Metzinger, 2009; Blanke, 2012). The sense of agency is the sense of being the author of generated actions or thoughts, and includes the feeling of being in control of own body movements and thoughts (Blanke & Metzinger, 2009; Frith, Blakemore, & Wolpert, 2000; Gallagher, 2000; Jeannerod, 2003; Pacherie, 2008; Tsakiris, Prabhu, & Haggard, 2006). While the sense of embodiment has been recognized to crucially depend on the accurate integration of body-related multimodal sensory information (vision, touch, sound, proprioception, vestibular signals, visceral signals) (Blanke, 2012; Ehrsson, 2007; Lenggenhager, Tadi, Metzinger, & Blanke, 2007), the sense of agency involves a strong efferent component as it depends on integration of centrally generated motor commands for voluntary actions and sensory consequences of those actions (Blakemore, Frith, & Wolpert, 1999; David, Newen, & Vogeley, 2008; Tsakiris et al., 2006; Wolpert & Ghahramani, 1995).

As the body is normally perceived to be always there and usually inseparable from the mind (Merleau-Ponty, 1962), it has been until recently difficult to experimentally manipulate the components of bodily-self consciousness described above. Better understanding became possible through the analysis of several neurological and psychiatric conditions, where the sense of body is altered. Today, with technological advances of video, virtual reality and robotics, cognitive neuroscience has developed powerful approaches to investigate separate components of bodily self-consciousness by inducing “bodily illusions” through on-line presentation of conflicting sensory information regarding one’s own body. Studying perceptual illusions is not merely a whimsical indulgence, but it is important for the studies of consciousness as it allows us to investigate how the brain processes sensory information and gives rise to conscious perception. In the following two chapters I describe the main experimental paradigms and give a brief overview of the studies that investigated the sense of body ownership or the sense of agency through multisensory conflicts as well as through clinical cases with disorders of bodily self-consciousness.

1.2 THE SENSE OF BODY OWNERSHIP AND ITS DISTURBANCES

The sense of body ownership, i.e. the experience that my body and bodily sensations belong to me, depends on an accurate integration of continuously changing body-related multisensory information (Gallagher, 2000; Tsakiris, 2010). The term multisensory integration of bodily signals refers to the brain’s capacity to combine information from different sensory modalities in order to provide stable and coherent perception of our body and its surrounding and improve our reactions to potentially dangerous stimuli (Holmes & Spence, 2005). The sensory inputs are constantly weighted and integrated based on their reliability, so that the source of sensory input which varies the least is the most reliable source of information and thus biases the representation of the sensory event (Ernst & Bülthoff, 2004; Pouget, Deneve, & Duhamel, 2002). Usually, vision is the most reliable source of information among the senses due to its high spatial resolution (however, the reliability depends on the context (Holmes & Spence, 2005)) and thus strongly biases perception. According to the principles of multisensory integration (Stein & Stanford, 2008), stimuli that occur closer in space or time are more strongly integrated. The integration is also stronger, when the single unimodal inputs are weaker – an effect that is termed inverse efficiency (Stein & Stanford, 2008). The integration of bodily signals in general follows the rules of multisensory integration of exteroceptive stimuli, but in addition also requires the concurrent processing of proprioceptive information about the body position, imposing additional restriction to the integration processes (Blanke, Slater, & Serino, 2015).

The bodily multisensory and motor signals are further combined with more stable, pre-existing internal body representations, such as perceptual, conceptual and semantic knowledge of the body (Carruthers, 2008; Frederique de Vignemont, 2010; Longo, Azañón, & Haggard, 2010; Serino & Haggard, 2010) to construct the sense of body ownership.

1.2.1 Experimental manipulations of body ownership

Presenting conflicting multisensory information about the location and appearance of one's body or body parts can temporally modify the sense of body ownership. An extensively used experimental paradigm to manipulate the sense of ownership for a hand is the rubber hand illusion (RHI) (Botvinick & Cohen, 1998). In this paradigm, the participants see a rubber hand positioned in front of them, while their own hand is hidden from their view (**Figure 1**). When both the rubber hand and the participants' hidden hand are stroked in synchrony, participants usually report to feel as if the rubber hand is their own hand (Botvinick & Cohen, 1998). The illusion is induced due to the dominant role of vision over the proprioceptive signals, and results in self-attribution of the rubber hand, referral of touch to the rubber hand, and the percept that the real hand is closer to the rubber hand (proprioceptive drift) (Botvinick & Cohen, 1998; Costantini & Haggard, 2007).

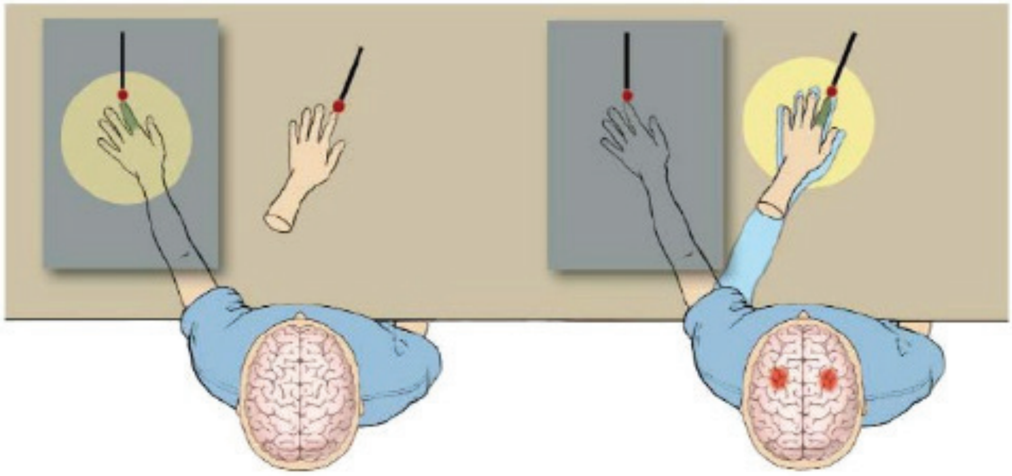

Figure 1. The rubber hand illusion setup. LEFT: The participant's left hand is hidden from his view and touched in synchrony with the rubber hand, positioned in front of him. RIGHT: Synchronous visuo-tactile stimulation results in a subjective feeling that the rubber hand is a part of own body, and in a mislocalization (proprioceptive drift) of the stroked hand towards the rubber hand (Botvinick & Cohen, 1998). Figure by Litwack Illustration studio 2004.

It has been shown that the RHI decreases with longer asynchronies between visual and tactile stimulation, with larger spatial distances between the real and the stroked hand (Ehrsson, Spence, & Passingham, 2004; Lloyd, 2007), with decreased visuo-anatomical resemblance (Haans, Ijsselsteijn, & de Kort, 2008; Tsakiris, Carpenter, James, & Fotopoulou, 2010; Tsakiris & Haggard, 2005), mismatching hand laterality (Tsakiris & Haggard, 2005) and larger incongruence in the posture between the rubber and real hand (Costantini & Haggard, 2007; Pavani, Spence, & Driver, 2000). The strength of the illusion is most commonly measured with a questionnaire and assessment of proprioceptive drift (Botvinick & Cohen, 1998; Lenggenhager et al., 2007; Tsakiris & Haggard, 2005), although reaction time tasks (Aspell, Lavanchy, Lenggenhager, & Blanke, 2010; Aspell, Lenggenhager, & Blanke, 2009; Pavani et al., 2000; Salomon, van Elk, Aspell, & Blanke, 2012; Charles Spence, Pavani, & Driver, 2004) and physiological measures, such as skin conductance (Armel & Ramachandran, 2003; Ehrsson, 2007; Petkova & Ehrsson, 2008; Romano, Pfeiffer, Maravita, & Blanke, 2014), temperature (Moseley et al., 2008; Rohde, Wold, Karnath, & Ernst, 2013; Salomon, Lim, Pfeiffer, Gassert, & Blanke, 2013) and histamine reactivity (Barnsley et al., 2011) have also been used.

The RHI has been successfully adapted to study the sense of ownership for feet (Brugger, Lenggenhager, & Giummarra, 2013), legs (see **Article 1**: Pozeg, Galli, & Blanke, 2015), face (Sforza, Bufalari, Haggard, & Aglioti, 2010; Tsakiris, 2008) and whole body (Ehrsson, 2007; Lenggenhager et al., 2007; Slater, Spanlang, Sanchez-Vives, & Blanke, 2010). In the so-called full-body (or out-of-body) illusions (FBI), the tactile stimulation is applied to the participants' back or chest while they simultaneously view through a head mounted display (HMD) a video or virtual reality simulation of being touched from an outside visuo-spatial perspective (**Figure 2**) (Ehrsson, 2007; Lenggenhager et al., 2007). Although the experimental use of the RHI paradigm (or its modified versions for other body parts) has accumulated an important knowledge about the brain mechanisms underlying the sense of body ownership, induction of the full body illusions has shown to be specifically important to investigate global bodily self-consciousness. It thus enables to experimentally study the aspects (global ownership, self-location, first person perspective) which are central to the representation of the self as an unitary and coherent whole and not only a sum of body parts (Blanke & Metzinger, 2009; Ehrsson, 2007; Lenggenhager et al., 2007).

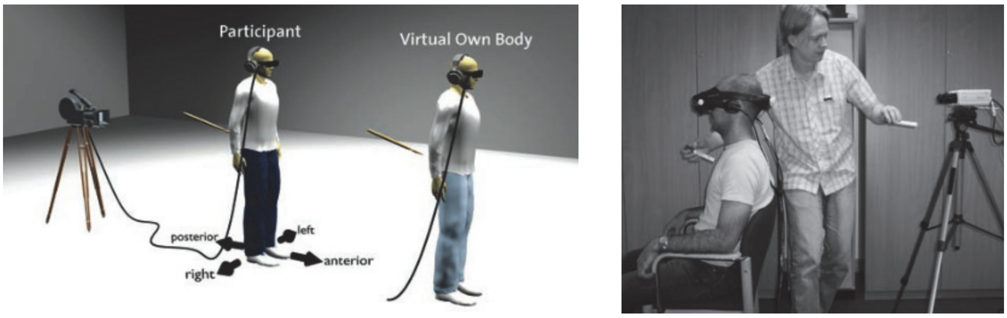

Figure 2. FBI setups. LEFT: A video-camera is positioned 2 meters behind a participant and films the participant's back, while the experimenter touches the participant's back with a stick. The participant thus sees his own virtual body being touched in front (from a third-person viewpoint) either in real-time or delayed (Lenggenhager et al., 2007). RIGHT: Through a head-mounted display, the participant sees his own back, filmed by a camera standing 2 meters behind. The experimenter repeatedly moves two sticks in synchrony or asynchrony, one towards the camera, and the other to touch the participant's chest (Ehrsson, 2007).

A few studies, which investigated underlying neural mechanisms of partial and global body ownership show large overlaps of activated areas associated with the sense of ownership, however differences have also been reported between partial and global ownership. The brain activity associated with the integration of visual, tactile and proprioceptive information in the RHI has been found in several brain regions, including ventral intraparietal sulcus (IPS), ventral premotor cortex (vPMC), inferior parietal cortices, lateral occipital complex, operculum, and cerebellum (Ehrsson, Holmes, & Passingham, 2005; Ehrsson et al., 2004; Makin, Holmes, & Zohary, 2007), whereas the vPMC (Ehrsson et al., 2005, 2004) and the posterior insula (Tsakiris, Hesse, Boy, Haggard, & Fink, 2007) have been specifically associated with the conscious experience of illusory ownership for the rubber hand. The fMRI studies of FBI showed an association between the sense of ownership for a virtual body with the activity in the bilateral vPMC, left IPS, left putamen (Guterstam, Björnsdotter, Gentile, & Ehrsson, 2015; Petkova, Björnsdotter, et al., 2011) and right extrastriate body area (Guterstam et al., 2015; Ionta et al., 2011), which is also involved in processing of human bodies (Downing, Jiang, Shuman, & Kanwisher, 2001; Urgesi, Candidi, Ionta, & Aglioti, 2007).

1.2.2 DISTURBED BODY OWNERSHIP IN CLINICAL CONDITIONS

The partial or global sense of body ownership may be disturbed in various neurological conditions (Critchley, 1950). For example, patients suffering from somatoparaphrenia manifest the delusion of disowning their left-sided body parts, most often their hand and arm due to the brain damage of the right parieto-temporal and insular regions (Bottini, Bisiach, Sterzi, & Vallar, 2002; Gerstmann, 1942; Romano, Gandola, Bottini, & Maravita, 2014; Vallar & Ronchi, 2009). Another disorder of partial body ownership is the delusion of a supernumerary phantom limb where the patient experiences to have an additional limb (Guterstam, Petkova, & Ehrsson, 2011; Halligan, Marshall, & Wade, 1993; McGonigle et al., 2002). One case report showed that this delusion was associated with a lesion in the supplementary motor area, (McGonigle et al., 2002) the region otherwise responsible for internal generation of movements and importantly, also involved in the neural network of bodily self-consciousness (Ionta, Martuzzi, Salomon, & Blanke, 2014).

The sense of body ownership can also be severely altered due to a partial or complete disconnection of sensory and motor nerves innervating a body part. The most drastic example of disconnection is limb amputation, where a body part is completely removed. Amputees often experience a phantom limb, i.e. a vivid sensation that the amputated limb is still present, is moving, or is painful (phantom pain) (Katz & Melzack, 1990; Melzack, 1989, 1992; Ramachandran, 1998). These phantom sensations are now widely considered to result from cortical reorganization of the somatosensory and motor regions (Flor et al., 1995; Ramachandran & Hirstein, 1998). Experiences of phantom limbs and phantom pain can also emerge after spinal cord injury (SCI) where the lesion of the spinal cord may cause a massive disconnection between the central nervous system and periphery, resulting in partial or complete loss of sensory and motor functions below the lesion site (Melzack & Loeser, 1978; Siddall, Taylor, McClelland, Rutkowski, & Cousins, 1999; Werhagen, Hultling, & Molander, 2006). Apart from phantom sensations, chronic SCI is also a relevant candidate for the study of the mechanisms of bodily-self consciousness. However, although the prevalence of SCI is relatively high (Lee, Cripps, Fitzharris, & Wing, 2014), only few studies investigated the sense of body ownership in SCI by using the RHI paradigm. For example it has been shown that although the SCI patients in general reported disturbances in bodily self-consciousness, they did not differ from healthy controls in the subjective experience of RHI. On the contrary, in comparison to controls, the SCI patients did not show proprioceptive hand mislocalization (Lenggenhager, Pazzaglia, Scivoletto, Molinari, & Aglioti, 2012; Scandola et al., 2014). Moreover, touching the patient's face in synchrony with the rubber hand also proved to be sufficient to induce the illusion, but only in SCI patients with tetraplegia, indicating SCI-related brain plasticity (Scandola et al., 2014).

We have investigated the sense of global body ownership and the sense of leg ownership in patients with paraplegia, using the FBI paradigm, and a novel version of the RHI, adapted to study leg ownership. We found that the SCI patients showed normal global body ownership in the FBI paradigm. However, they showed reduced proneness to experience illusory leg ownership. Importantly, the strength of the illusion was negatively correlated to the duration of the sensorimotor deprivation, pointing to a possible SCI-related plasticity in multimodal regions associated with processing of the body-related sensory information (see **Article 2,** Pozeg et al., in preparation).

Dramatic disturbances affecting the global sense of body ownership can be observed in autoscopic phenomena – illusory own body perceptions or duplications that affect the entire body. They include *autoscopic hallucination* (AH), *out-of-body experiences* (OBE), *heautoscopy* (HAS), and *feeling of a presence* (FoP) (Blanke & Mohr, 2005; Brugger, Regard, & Landis, 1997; Brugger, 2002). In an AH, patients see their own body in extrapersonal space, as in a mirror, but they perceive themselves to be located within their physical body. Thus the sense of self-location and first person perspective remain intact. The etiology of AH reported in the literature is mostly focal epilepsy, migraine, ischemic and neoplastic brain damage in parieto-occipital lobes (Brugger et al., 1997; Brugger, 2002; Heydrich & Blanke, 2013). In an OBE the patients experience being outside of their physical body and seeing it from an elevated, third person perspective. Great variety of OBE etiologies has been reported (Blanke, Landis, Spinelli, & Seeck, 2004; Brugger, 2002; Devinsky, Feldmann, Burrowes, & Bromfield, 1989) and the illusion has been associated with abnormal vestibular sensations (Blanke et al., 2004; Kaliuzhna, Vibert, Grivaz, & Blanke, 2015; Lopez, Halje, & Blanke, 2008). Nevertheless, lesion analysis of nine patients who experienced OBE showed the maximum lesion overlap at the right angular gyrus and superior temporal gyrus, linking the OBE to abnormal integration of body-related multisensory (visual, tactile, proprioceptive and vestibular) information (Ionta et al., 2011). HAS has been defined as an intermediate form between AH and OBE; the patients experience seeing their own body in extrapersonal space, however their sense of self-location shifts between their physical body and their double. HAS have been reported in patients suffering from temporal lobe epilepsy, insular tumors, migraines and schizophrenia and has been linked to mostly left temporal, temporo-parietal, and insular lesions (Brugger et al., 1997; Brugger, 2002; Heydrich & Blanke, 2013). Another type of autoscopic phenomena is FoP, marked by only somesthetic sensation of a presence of another person in the near extracorporeal space and it does not include any visual hallucinations. The feeling is often accompanied by the sense of familiarity towards the presence (Brugger et al., 1997; Critchley, 1950). FoP has been frequently described by healthy persons who have been in extreme environments, sensory or social deprivation (Brugger, Regard, Landis, & Oelz, 1999; Suedfeld & Mocellin, 1987). It is often reported by people who suffer from epileptic seizures, stroke, brain tumors, migraine, and psychiatric conditions (Blanke, Arzy, & Landis, 2008; Brugger, Regard, & Landis, 1996). We have recently showed that FoP is associated with lesions in the temporoparietal, frontoparietal, and insular cortex, is related to the deficits in sensorimotor integration, and is likely to be caused by misperception and misattribution of own sensorimotor signals (see **Article 5**: Blanke et al., 2014).

1.3 SENSORIMOTOR INTEGRATION AND THE SENSE OF AGENCY

Besides body ownership, the sense of agency has been recognized as a central feature of the subjective experience of the self (David et al., 2008; Gallagher, 2000; Newen & Vogeley, 2003). It has been defined as the sense of being the one who is causing an action or generating a thought, including the sense of being in control over own movements and thoughts (Blanke & Metzinger, 2009; Frith et al., 2000; Gallagher, 2000; Jeannerod, 2003; Pacherie, 2008; Tsakiris et al., 2006). It enables one to distinguish the actions that have been self-generated from those that have been produced by another agent. As such, it importantly contributes to the construction of the sense of self (Gallagher & Meltzoff, 1996; Synofzik, Vosgerau, & Newen, 2008; Vosgerau & Newen, 2007). The most basic sense of agency originates from sensorimotor processes, as it depends on causal link between an action and the sensory consequences of that action (Synofzik et al., 2008). A predominant interpretation of how the sense of agency arises is the central monitoring, predictive or comparator model (Blakemore, Wolpert, & Frith, 2002; David et al., 2008), based on early propositions of mechanism for oculomotor control (Helmholtz, 1866; Sperry, 1950) and internal forward models for sensorimotor integration and action control (Wolpert & Ghahramani, 1995). According to the comparator model, an efference copy or a prediction about the desired sensory state is issued with a motor command. This prediction is then compared with the respective sensory consequence. When they are congruent, the action is self-attributed, leading to the sense of agency. Contrarily, in the case of incongruence between the prediction and sensory outcome, the cause of the action is attributed to the external environment (**see Figure 3**).

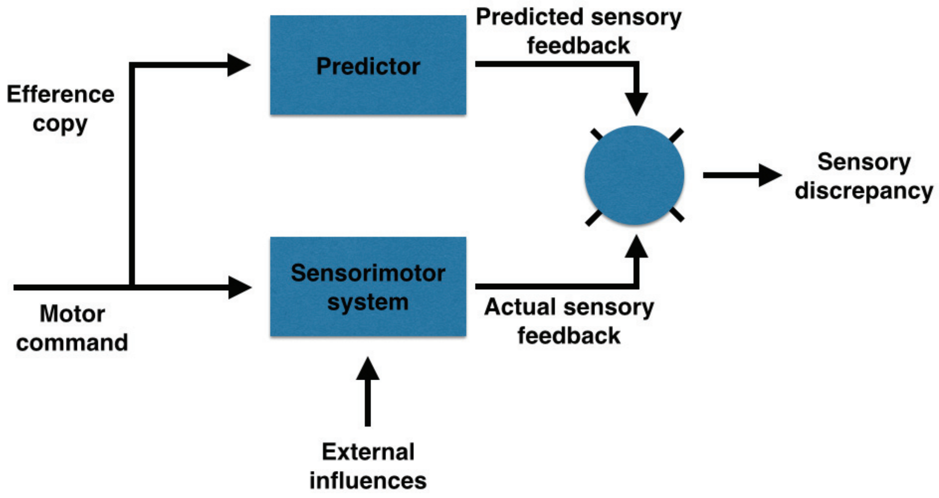

Figure 3. The comparator model. Based on a motor command, a prediction signal (efference copy) is issued, which is then compared with the actual sensory feedback. In case of mismatch, the cause of the sensory event is attributed to an external agent. The figure is adapted from Schubotz (2007).

1.3.1 EXPERIMENTAL MANIPULATIONS OF THE SENSE OF AGENCY

In a classical experimental paradigm that investigates the sense of agency, a subject is performing an action, while the sensory consequence of the action is manipulated, usually by providing a temporal or spatial deviation of an actual sensory outcome. For example, in one of the earliest experiments (Nielsen, 1963), a subject was drawing a line with a pencil, while in the provided visual feedback, he saw either his own hand or an "alien", i.e. the experimenter's hand, drawing the line as being spatially deviated (**Figure 4**). The subjects were unaware that they were adjusting their movements to the false feedback, but only to a certain degree of deviation, when they recognized that it was not themselves who drew the line. This paradigm has been replicated several times and has evolved into numerous adaptations, where the feedback is manipulated in other sensory modalities or the role of motor signals is investigated, such as in passive or active movements (for a review see David et al., 2008).

A large body of evidence shows that the self-produced sensations are attenuated on a perceptual as well as neural level. For example, inserting a temporal delay between a movement and tactile feedback during self-generated tactile stimulations leads to an increment in perceived intensity of the tactile stimuli (Blakemore et al., 1999; Blakemore, Wolpert, & Frith, 1998; Weiskrantz, Elliot, & Darlington, 1971).

Moreover, a recent fMRI study showed that tactile-related cortical response to self-administered tactile stimulation is reduced in the secondary somatosensory cortex, and that the attenuation is the largest when the movement and tactile feedback are temporally synchronized (Shergill et al., 2013). Similar mechanisms of sensory suppression of self-produced actions have been found in visual modality for self-initiated visual stimuli (Gentsch & Schütz-Bosbach, 2011; Hughes & Waszak, 2011), in auditory modality during vocal activity (Creutzfeldt, Ojemann, & Lettich, 1989; Ford et al., 2001; Fu et al., 2006; McGuire, Silbersweig, & Frith, 1996; Müller-Preuss & Ploog, 1981), walking (van Elk, Salomon, Kannape, & Blanke, 2014) and heart-beat sounds (van Elk, Lenggenhager, Heydrich, & Blanke, 2014). The attenuation of sensory feedback to self-produced actions thus enables enhanced perception of novel, external events and provides a basic, pre-reflective mechanism for self-other distinction (Shergill et al., 2013).

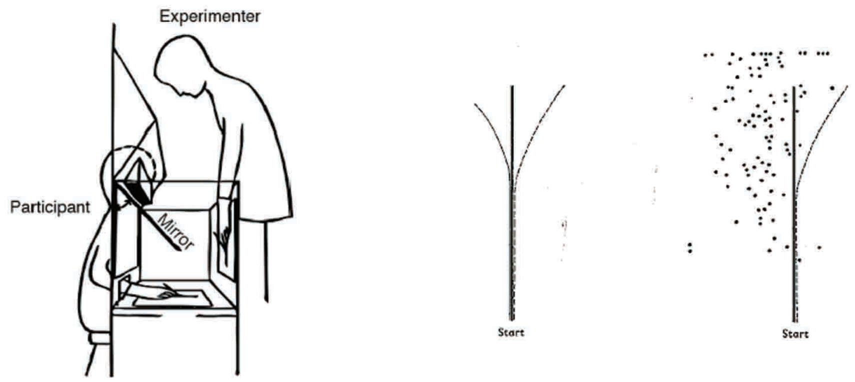

Figure 4. Experimental setup in the early agency study. LEFT: The participant was instructed to follow a straight line with a pencil, while he was receiving the visual feedback about his performance through a mirror screen. In the "alien hand" trials the mirror was without the participant's knowledge turned in the way that reflected the experimenter's hand, which first followed the line but soon started to deviate from it. MIDDLE: Participants had to follow the straight line; the dotted line represents deviation made by the experimenter, and the thin solid line a typical line drawn by the subject during the deviated visual feedback. RIGHT: The dots represent the ends of lines drawn by 20 subjects during the deviated visual feedback (Nielsen, 1963).

1.3.2 SELF-TOUCH: INTERACTION BETWEEN AGENCY AND OWNERSHIP

Self-touch represents a particular form of self-produced action, where the body part administrating tactile stimulation can be, at the same time, also the body part receiving the tactile input. Thus, during self-touch the body is the agent of the action, as well as the object of the performed action. During voluntary self-touch motor signals are integrated with multisensory feedback (simultaneous tactile cues from two different body surfaces and proprioceptive signals) and, as such, self-touch represents a unique interaction between the sense of agency and the sense of body ownership. It has been argued that self-touch importantly contributes to the generation and restoration of body representation (Schütz-Bosbach, Musil, & Haggard, 2009), as it has been shown that it ameliorates tactile perception in stroke patients with hemihypesthesia, i.e. unilateral reduced tactile sensitivity (Valentini, Kischka, & Halligan, 2008; Weiskrantz & Zhang, 1987), and left tactile extinction (Coslett & Lie, 2004). It has been shown to restore the sense of hand ownership in a patient with somatoparaphrenia (van Stralen, van Zandvoort, & Dijkerman, 2011). Self-touch also reduces the intensity of perceived thermal pain (Kammers, de Vignemont, & Haggard, 2010). The ability to discriminate self-generated tactile sensations from those that are externally produced is present already at birth (Rochat & Hespos, 1997). As such, self-touch is arguably crucial for the early development of basic self-awareness, as it enables one to differentiate one's own body from other objects and delineate boundaries between the self and others (Dieguez, Mercier, Newby, & Blanke, 2009; Gallagher & Meltzoff, 1996; Merleau-Ponty, 1962; Rochat & Hespos, 1997; Rochat, 1998; Schütz-Bosbach et al., 2009; van Stralen et al., 2011).

The relationship between self-touch and the sense of body can be experimentally studied with a tactile version of RHI (Ehrsson et al., 2005). In this non-visual adaptation of the classical RHI, a blindfolded participant sits at a table with his palms down. A rubber hand is placed between the participant's hands. The experimenter touches the rubber hand with one of the participant's fingers while simultaneously touching the participant's other hand. The participant thus receives tactile cues at the tip of his touch-administrating finger and on the dorsal part of his touch-receiving hand. When this "double" touch is temporally and spatially correlated, the participant experiences touching his own hand (self-touch illusion), while instead his hands are not in a physical contact (**Figure 5**). The illusion is also associated with proprioceptive mislocalization of the stroked hand towards the rubber hand (Aimola Davies, White, & Davies, 2013; Ehrsson et al., 2005; Hara et al., 2015; Pozeg, Rognini, Salomon, & Blanke, 2014; White, Aimola Davies, & Davies, 2011; White, Aimola Davies, Halleen, & Davies, 2010). The illusion of self-touch arises as a resolution of the conflict between proprioceptive signals and temporally matched double tactile information. As proprioceptive signals are generally less reliable, the synchronous double-touch, which is normally present during actual self-touch, biases the tactile-proprioceptive integration, and results in the interpretation that two synchronous tactile events occurred at the same spatial location. Crossing the hands, a manipulation frequently used to influence the reliability of proprioceptive signals (Azañón & Soto-Faraco, 2008; Holmes, Sanabria, Calvert, & Spence, 2006; Shore, Spry, & Spence, 2002), significantly increases the strength of self-touch illusion (see **Article 3**: Pozeg et al., 2014).

Figure 5. Self-touch illusion in the tactile RHI. The experimenter touches the rubber hand with participant's index finger and in the same time touches the participant's other hand (Ehrsson et al., 2005). The figure is reprinted from Pozeg et al. (2014).

Studies using the tactile RHI paradigm as described above, have focused on the investigation of passive self-touch, while in real-life, self-touch is normally generated by voluntary movements, and as such characterized by sensorimotor integration including predictive signals (efference copies). For this reason, we have explored the role of active self-touch in the experience of self-touch illusion and sense of hand ownership. This was possible through a custom-built robotic master-slave system (Hara et al., 2011), which allowed participants to control a handle of the master robot to touch a virtual hand, while the slave part of the robot, by copying the participant's movement trajectories and force, applied tactile stimulation to the participant's other hand (**Figure 6**). We have shown that the presence of motor signals (as in active self-touch) not only increased the sense of agency, but also elicited stronger sensation of self-touch illusion and sense of hand ownership (see **Article 4**: Hara et al., 2015). The presence of efferent information and consequently additional sensorimotor correspondence between predicted and actual tactile information thus further strengthens the illusory sense that a virtual hand belongs to the self.

The same robotic platform was also used to extend the tactile RHI paradigm to study the role of active self-touch in the global self-consciousness, by adjusting the setup so the sensorimotor stimulation was applied to the trunk. In this setup, the blindfolded participant moved their arms, and thereby also moved the master device attached to their hand, in front of them. The trajectories of these movements were copied to the slave robot, which in real-time applied tactile stimuli to the participant's back (**Figure 6**).

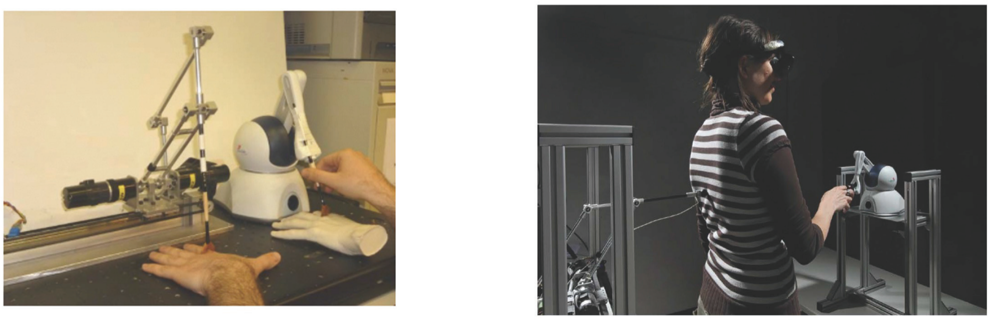

Figure 6. Master-slave robotic setup. LEFT: The master-slave robotic system used to induce the self-touch illusion. The participant moves the brush attached to the master device to touch the rubber hand. The slave robot applies the strokes to the participant's other hand with the same velocity and force (Hara et al., 2011). RIGHT: Blindfolded participant moves the master device in front of him, while the slave robot behind him copies his movements and touches the participant's back (Blanke et al., 2014).

Tactile feedback at the participants' back synchronized with participants' movements resulted in the experience of illusory self-touch, increased sense of agency for the tactile event and also biased the sense of self-location forward, in front of the physical body. However, when a temporal deviation of 500 ms was inserted between the participant's movements and received tactile feedback, subjects reported decreased illusory self-touch, decreased sense of agency, and also an illusory presence of somebody behind them (see **Article 5**: Blanke et al., 2014). Thus in accordance with the prediction error model, the experimentally induced incongruence between sensorimotor predictions and actual sensory outcome caused the participants to misperceive the source and identity of own sensorimotor signals and misattribute them to an external agent. These findings show that accurate sensorimotor integration is not only necessary for the sense of agency but also for a normal bodily awareness. The observed results also share similarities with symptoms of schizophrenia, where disturbed sense of agency and blurring of self-other boundaries are the core characteristics of the disease (see next chapter).

1.3.3 DISTURBED SENSE OF AGENCY IN CLINICAL CONDITIONS

Impaired sense of agency for own limb movements is a central feature of the alien-hand syndrome, also known as anarchic hand syndrome, or strange hand sign. This rare neurological disorder is characterized by the patient recognizing her arm movements as foreign, involuntary and out of control. These movements are usually purposeful, and goal-directed, but not perceived as initiated by the patient's own intentions or will. The alien hand sometimes interferes with the willed actions of the patient's unaffected hand (Aboitiz et al., 2003; Fisher, 2000; Hidalgo-Borrajo, Belaunzaran-Mendizábal, Hernáez-Goñi, Tirapu-Ustárroz, & Luna-Lario, 2009; Marchetti & Salla, 1998). Distinctions between alien and anarchic hand have been made based on reported hand disownership. In the anarchic hand syndrome the patient denies any sense of agency for the affected hand's actions but he still recognizes it as belonging to himself. The alien hand syndrome has been defined to include both, loss of agency and denial of ownership for the affected hand (Aboitiz et al., 2003; Biran & Chatterjee, 2004; Marchetti & Salla, 1998; Scepkowski & Cronin-Golomb, 2003). The disorder has been mostly associated with disruption of interhemispheric connectivity in callosotomy and a damage to the anterior callosal fibers, but also with lesions in the supplementary motor area, medial frontal cortex and anterior cingulate cortex (Aboitiz et al., 2003; Biran & Chatterjee, 2004; Goldberg, Mayer, & Toglia, 1981; Marchetti & Salla, 1998; Scepkowski & Cronin-Golomb, 2003).

Impaired sense of agency has also been observed in patients with schizophrenia. This psychiatric disorder is probably one of the most devastating, affecting around 1% of world population, manifested in a broad symptomatology, including auditory verbal hallucinations, delusions of control, thought withdrawal, and thought insertion, i.e. the symptoms where disrupted sense of agency is most obvious (American Psychiatric Association, 2000; Schneider, 1959). Based on the comparative model, it has been suggested that certain positive symptoms in schizophrenia are due to deficits in the internal predictive models (Feinberg, 1978; Frith et al., 2000; Frith & Done, 1988; Frith, 1992). Several studies have in fact demonstrated that patients with schizophrenia have deficits in sensory attenuation of self-generated motor actions (Blakemore et al., 2002; Ford, Roach, Faustman, & Mathalon, 2008; Shergill et al., 2014; Shergill, Samson, Bays, Frith, & Wolpert, 2005; Teufel, Kingdon, Ingram, Wolpert, & Fletcher, 2010) and attribution of agency (Daprati et al., 1997; Franck et al., 2001). The comparator model has been used to explain auditory-verbal hallucinations, which according to the model are misattributed own inner speech, perceived by the patient as originating from an external agent. This proposition is supported by a large body of studies showing that the patients with auditory verbal hallucinations have reduced suppression of cortical response during own speech as compared to healthy subjects (David, 1994; Ford & Mathalon, 2004, 2005; Ford et al., 2001; Ford, Roach, Faustman, & Mathalon, 2007; Gould, 1949; Green & Kinsbourne, 1990; Heinks-Maldonado et al., 2007; Inouye & Shimizu, 1970; Junginger & Rauscher, 1987). Impaired predictive mechanisms have also been proposed to underlie the phenomenon of thought insertion, by considering thoughts as an analogue of motor actions (Feinberg, 1978; Frith & Done, 1988; Frith, 1992). However, despite offering a parsimonious explanation, the comparator model lacks sufficient supportive evidence to explain the loss of thought agency in the delusions of thought insertion (Campbell, 1999; Spence, 2001; Vosgerau & Newen, 2007). Recently, the positive symptoms of schizophrenia have been understood within a hierarchical Bayesian or predictive model framework (Apps & Tsakiris, 2014; Clark, 2013; Fletcher & Frith, 2009). According to this theory, the internal model about the world is built based on the prediction-error signals communicated from the lower to the higher-level system, and conversely, prior beliefs are provided to the lower level systems through the feedback from the higher levels (Clark, 2013; Fletcher & Frith, 2009; Friston, Kilner, & Harrison, 2006; Summerfield & Koechlin, 2008). Therefore, inferences about an external event are made through a constant interaction between basic sensory experiences and one's beliefs. Thus, a perceptual anomaly accompanying impaired prediction error mechanism may propagate to higher levels, and influence formation of delusional beliefs, which in turn bias the perception (Corlett, Taylor, Wang, Fletcher, & Krystal, 2010; Fletcher & Frith, 2009; Schmack et al., 2013).

In a recent study (see **Article 6**) we investigated how a perturbation of the prediction error mechanism in healthy subjects influences their sense of agency for mental content and induces delusions-like beliefs. Using the same robotic platform as in above described studies (Blanke et al., 2014; Hara et al., 2015) we created an incongruence between sensory predictions of own motor actions and actual sensory outcome, while participants performed verbal fluency and verbal memory tasks. They were later asked to make agency judgments regarding the produced mental content. In line with the predictive model framework, the participant manifested reduced sense of agency for their own movement when provided sensory feedback to their motor actions was temporally deviated (as compared to synchronous mode). In addition, such sensorimotor mismatch also resulted in reduced sense of agency for own thoughts (assessed by behavioural and subjective measures). We link these findings to the role of prediction error in the formation of delusional beliefs and discuss them within the predictive model framework (see **Article 6** and General discussion of the thesis).

2 OVERVIEW OF THE INCLUDED STUDIES

The aim of this chapter is to give a brief summary of the scientific articles included in the thesis and shortly provide the main motivation, research question, methodology and findings of each article. The results are then further discussed and integrated in the Discussion section. The publications and their summaries are not listed in the chronological order as they were published, but are instead presented in an order that is content-wise meaningful. I significantly contributed to the following publications:

Pozeg, P., Galli, G., & Blanke, O. (2015). Those are Your Legs: The Effect of Visuo-Spatial Viewpoint on Visuo-Tactile Integration and Body Ownership. *Frontiers in Psychology*, *6*. Contribution: designing and conducting the experiment, analysis and writing.

Pozeg, P., Paluel, E., Ronchi, R., Solca, M., Al Khodairy, A., Kassouha, A., Jordan, X., & Blanke, O. Body ownership in paraplegia: Implications for pain management and neurorehabilitation (in preparation). Contribution: designing and conducting the experiments, analysis and writing.

Pozeg, P., Rognini, G., Salomon, R., & Blanke, O. (2014). Crossing the hands increases illusory self-touch. *PloS One*, *9*(4). Contribution: designing and conducting the experiments, analysis and writing

Hara, M., Pozeg, P., Rognini, G., Higuchi, T., Fukuhara, K., Yamamoto, A., Blanke, O., & Salomon, R. (2015). Voluntary self-touch increases body ownership. *Frontiers in Psychology*, *6*. Contribution: designing experiments, analysis and writing.

Blanke, O., Pozeg, P., Hara, M., Heydrich, L., Serino, A., Yamamoto, A., Higuchi, T., Salomon, R., Seeck, M., Landis, T., Arzy, S., Herbelin, B., Bleuler, H., & Rognini, G. (2014). Neurological and Robot-Controlled Induction of an Apparition. *Current Biology*, 24(22). Contribution: designing and conducting the experiments, analysis of behavioral data and writing.

Pozeg, P., Serino, A., Rognini, G., & Blanke, O. Sensorimotor manipulation of thought agency and thought insertion in healthy subjects (in preparation). Contribution: designing and conducting the experiments, analysis and writing.

2.1 PART 1: THE SENSE OF BODY OWNERSHIP

2.1.1 ***ARTICLE 1****: THOSE ARE YOUR LEGS: THE EFFECT OF VISUO-SPATIAL VIEWPOINT ON VISUO-TACTILE INTEGRATION AND BODY OWNERSHIP*

A coherent sense of own body depends on successful integration of multimodal bodily signals and their congruence with pre-existing body representation (Blanke, 2012; Carruthers, 2008; Longo et al., 2010). To ensure optimal perception and action, it is important that the multisensory information is coded within the egocentric coordinate system, a process requiring a visuo-spatial viewpoint centred at one's own physical body (first-person viewpoint, sometimes also called first-person perspective) (Blanke & Metzinger, 2009). However, the studies on body ownership yielded diverging results of whether the first person visuo-spatial viewpoint is necessary for the sense of body ownership (Ehrsson, 2007; Lenggenhager et al., 2007; Petkova, Khoshnevis, & Ehrsson, 2011; Pfeiffer, Schmutz, & Blanke, 2014). Moreover, the role of the first-person viewpoint in the multisensory integration and body ownership has only been investigated for the entire body (Maselli & Slater, 2014; Petkova, Khoshnevis, et al., 2011; Pfeiffer et al., 2014) or hands (Costantini & Haggard, 2007; Ehrsson et al., 2004; Guterstam et al., 2011; Lloyd, 2007; Tsakiris & Haggard, 2005), but not for lower limbs. As many neuronal and functional differences exist between upper and lower extremities (van Elk, Forget, & Blanke, 2013) their multisensory representations may significantly differ. We therefore investigated how leg multisensory representation and sense of leg ownership depend on the visuo-spatial viewpoint, using a virtual leg illusion, a paradigm adapted from the RHI (Botvinick & Cohen, 1998). During the experiment the participant sat in a chair and wore an HMD. A pair of dummy legs was placed on another chair, mimicking the usual sitting position. A camera was recording the virtual legs from a height and position that corresponded to the participant's visuo-spatial viewpoint. The real-time video was projected onto the HMD. The experimenter simultaneously tapped the upper part of the participant's left leg and corresponding part of the left virtual leg. Participants saw the virtual legs in their first-person viewpoint or rotated by 90 degrees, while the visuo-tactile tapping was synchronous or asynchronous. In the control conditions, subjects viewed wooden objects instead of the virtual legs. We measured the strength of visuo-tactile integration through crossmodal congruency effect (CCE) task (Spence, Pavani, & Driver, 1998) and the subjective sense of illusory leg ownership with a questionnaire. We showed that first-person visuo-spatial viewpoint significantly increased the strength of visuo-tactile integration and the sense of leg ownership, and that this increase was body specific. The findings are further discussed in section 3.1.

2.1.2 *ARTICLE 2: BODY OWNERSHIP IN PARAPLEGIA: IMPLICATIONS FOR PAIN MANAGEMENT AND NEUROREHABILITATION*

Spinal cord injury (SCI) can cause a permanent disconnection of sensory and motor fibers, leaving the body below the level of the injury paralyzed. Chronic sensorimotor deprivation due to SCI leads to structural and functional changes at the cortical and subcortical level, following a somato-topological organization (Henderson, Gustin, Macey, Wrigley, & Siddall, 2011; Wrigley et al., 2009). The reorganization in primary somatosensory and motor cortex has been associated with phantom sensations, ranging from the feeling of touch, thermoception, to movement and pain (Jensen, Krebs, Nielsen, & Rasmussen, 1983; Wrigley et al., 2009). However, only few studies have investigated how chronic deinnervation due to SCI influences the subjective experience of one's own body (Lenggenhager et al., 2012; Lenggenhager, Scivoletto, Molinari, & Pazzaglia, 2013; Scandola et al., 2014; Scandola, Aglioti, Pozeg, Avesani, & Moro, 2016). We have therefore studied how chronic sensorimotor deprivation affects the global body ownership, using adapted versions of the FBI paradigm (Lenggenhager et al., 2007), and how it affects leg ownership, using the virtual leg illusion (VLI) paradigm (Pozeg et al., 2015). As these illusions showed to increase the subjective pain threshold and reduce galvanic skin response to painful stimuli in healthy subjects (Hänsel, Lenggenhager, von Känel, Curatolo, & Blanke, 2011; Romano, Llobera, & Blanke, 2016; Romano, Pfeiffer, et al., 2014), we in addition tested whether the applied multisensory conflict had analgesic properties for the SCI patients with neuropathic pain. We tested 20 patients with paraplegia and 20 age and gender matched healthy controls. The strength of the FBI and VLI illusions were tested with questionnaires, and the changes in the actual neuropathic pain levels were assessed with a visual analogue scale. No differences were found between SCI patients and controls in their experiences of the FBI. On contrary, we found that the SCI subjects less readily integrated conflicting multisensory information to construct an illusory sense of ownership for lower limbs, and that the paradigm showed marginal analgesic effects for neuropathic pain. Importantly, the strength of the leg illusion in SCI group decreased with longer time since injury, which has an important implication for planning early rehabilitation and pain management protocols. These findings are further discussed in the section 3.2 and the general discussion of the thesis.

2.2 PART 2: SELF-TOUCH

2.2.1 *ARTICLE 3: CROSSING THE HANDS INCREASES ILLUSORY SELF-TOUCH*

The tactile modality one hand enables the most extensive interface with the external world, while, on the other hand, it plays an important role in constructing the representation of own body in the multisensory environment (Berlucchi & Aglioti, 1997; Blanke, 2012; Serino et al., 2013). This is especially the case for self-touch, where the integration of tactile, proprioceptive and motor signals importantly contributes to the basic self-awareness and self-other distinction (Gallagher & Meltzoff, 1996; Merleau-Ponty, 1962; Schütz-Bosbach et al., 2009). It has repeatedly been shown that manipulating proprioceptive signals, such as a crossing the hands, hinders tactile-proprioceptive integration and affects tactile perception (Medina & Coslett, 2010; Shore et al., 2002). Here we investigated how crossing the hands affects the illusory perception of self-touch in the tactile RHI paradigm (Ehrsson et al., 2005). Blindfolded participants were passively touching (guided by the experimenter) a rubber hand with their index finger, while in the same time the experimenter was touching the dorsal part of their other hand. Their hands were either uncrossed or crossed over midline position, and the tactile stimulation (index finger, dorsal part of the hand) was either synchronous or asynchronous. The strength of the illusion was assessed with questionnaire ratings and proprioceptive drift. The results showed that synchronous stimulation led to increased self-touch illusion, and that crossing the hands boosted the illusion further. Additional experiments showed that the crossed hands-related increase in illusory touch was not due to a generally unfamiliar hand posture and that it was equally strong regardless at which location the hands were crossed. Finally, the crossed hands effect was not observed in the classical version of the RHI. These findings are further interpreted and discussed in section 3.3.

2.2.2 *ARTICLE 4: VOLUNTARY SELF-TOUCH INCREASES BODY OWNERSHIP*

The sense that our body belongs to us (body ownership) and that we are the agents of our own actions (sense of agency) are the fundamental aspects of the bodily self-consciousness and strongly depend on successful integration of multisensory and sensorimotor signals (Blanke & Metzinger, 2009; Blanke, 2012; Gallagher, 2000). A particular case of interaction between the sense of body ownership and sense of agency is voluntary self-touch, during which the body is at the same time an agent and an object of perception. The role of self-touch in the sense of body ownership has been experimentally investigated by using the tactile version of the RHI (Aimola

Davies et al., 2013; Ehrsson et al., 2005; Pozeg et al., 2014; White et al., 2010), however, these studies have been focused on passive self-touch. Despite the fact that self-touch is very frequent in everyday life and that its contribution to the development and restoration of structural body representation has been widely recognized (Gallagher & Meltzoff, 1996; Merleau-Ponty, 1962; Rochat & Hespos, 1997; Schütz-Bosbach et al., 2009; van Stralen et al., 2011), the role of voluntary self-touch in the sense of body ownership has not yet been well understood. We therefore compared how active and passive self-touch influence the illusory perception of self-touch in a novel version of tactile RHI, using a robotic master-slave system (Hara et al., 2011) and virtual reality, which allowed participants to self-administer tactile stimulation. In the first two experiments we manipulated the mode of tactile administration (active and passive) and synchrony between the administered and received touch (synchronous, asynchronous) in the absence or presence of visual feedback. In a third experiment, we compared the active and passive self-touch to the touch administered by the experimenter in a classic RHI. We measured the strength of illusory self-touch and hand ownership with a questionnaire and proprioceptive drift. We showed that the illusory self-touch as well as illusory hand ownership significantly increased with active self-touch. These findings confirm the important contribution of sensorimotor signals to the sense of body ownership.

2.3 PART 3: THE SENSE OF AGENCY AND DELUSIONS IN HEALTHY SUBJECTS

*2.3.1 **ARTICLE 5**: NEUROLOGICAL AND ROBOT-CONTROLLED INDUCTION OF AN APPARITION*

Aberrant integration of body-related multisensory information has been suggested to underlie several autoscopic phenomena - a group of hallucinations, where one sees its own physical body in an extrapersonal space, such as for example the out-of-body experience (Blanke & Mohr, 2005; Brugger et al., 1997; Brugger, 2002). A particular case of an abnormal body experience is the feeling of a presence (FoP), a strange sensation that someone is nearby when no one is actually present and can be seen (Critchley, 1950). FOP has been often reported by neurological and psychiatric patients (Brugger et al., 1996, 1997; Kasper, Kasper, Pauli, & Stefan, 2010), as well as by healthy individuals in extreme conditions (Brugger et al., 1999; Suedfeld & Mocellin, 1987). Two single case reports showed that electrocortical stimulation of the temporoparietal junction induced the FoP, and that the sensed presence followed the posture and gestures of the patient, indicating the involvement of the sensorimotor network in the generation of the phenomenon (Arzy, Seeck, Ortigue, Spinelli, & Blanke, 2006; Zijlmans et al., 2009). Here we investigated the sensorimotor hypothesis by first analyzing brain lesions of 12 neurological patients with FoP, and later by testing healthy subjects in a series of experimental paradigms. Analysis of brain lesions and associated neurological symptoms showed the maximum overlap at the insular, temporoparietal, and frontoparietal cortices, with the latter being significantly associated with the FoP. Next we conducted three behavioral experiments, using the master-slave robotic platform (Hara et al., 2011) in order to induce a mismatch between motor-based sensory predictions and actual sensory feedback, and therefore perturb sensorimotor integration. Blindfolded participants moved the master device in front of them, while trajectories and force of their movements were sent to the slave robot, which applied tactile stimuli in real time to the participant's backs. We manipulated the temporal delay between the participant's motor performance and the received tactile feedback. We showed that asynchronous stimulation (as compared to synchronous) induced an increased sensation of being touched by someone else and feeling of being in a presence of another person, as first spontaneously reported by participants and later assessed by questionnaire ratings. The experience of the FoP was also associated with a backward drift in self-location, as assessed by an implicit self-location task. Coherent with elevated FoP ratings, participants also estimated that more persons were present in the room in the asynchronous than in the synchronous stimulation condition. These results show that altered congruence between sensorimotor predictions and sensory feedback, due to brain damage or experimental manipulation, leads to misattribution of the source of own sensorimotor signals to an external agent and consequently results in the experience of the FoP. Finally, this study shows that experimentally induced sensorimotor mismatch in healthy subjects may temporarily evoke an experience resembling positive symptoms in schizophrenia (Mellor, 1970; Schneider, 1959).

*2.3.2 **ARTICLE 6**: SENSORIMOTOR MANIPULATION OF THOUGHT AGENCY AND THOUGHT INSERTION IN HEALTHY SUBJECTS*

A better understanding of self-consciousness can be obtained by investigating the disorders of self, amongst which schizophrenia might be the most severe self-disorder. It has been proposed that a central aspect of schizophrenia is the loss of the sense of agency, i.e. the ability to recognize and attribute a motor action, thought, or emotion, to its proper agent (Blakemore et al., 2002; Fletcher & Frith, 2009; Jeannerod, 2003), and is reflected in positive symptoms, such as auditory verbal hallucinations, delusions of control, and thought insertion (Schneider, 1959). Recently, certain symptoms of schizophrenia have been interpreted as a deficit in internal prediction models (Corlett et al., 2010; Fletcher & Frith, 2009). According to this hierarchical predictive coding view, we construct a model about the world in a probabilistic fashion, where the sensory signals are compared with prior predictions (beliefs) about the sensory event, and in case of mismatch, prediction errors are fed back in a hierarchical manner to update the predictions. Delusional beliefs, manifested as agency misattribution, are therefore formed due to abnormal integration between bottom-up, sensory signals and top-down, prediction signals. We previously showed that experimentally manipulating the sensory outcome of self-actuated movements with a robotic device reduced the sense of agency for self-produced tactile sensations and resulted in subjective, schizophrenia-like illusory sensations of being in the presence of another agent (Article 5: Blanke et al., 2014). Here, we investigated how the same robotically induced sensorimotor mismatch affects the sense of agency for thought processes in healthy subjects. We tested their sense of agency for self-produced words objectively through behavioural paradigms, and subjectively, through questionnaire ratings. Thus, in a series of three studies, the participants manipulated the master robot device while they were engaged in a verbal source-memory task (Study 1), verbal fluency task (Study 2) or word numerosity judgment task (Study 3). We showed that sensorimotor mismatch (asynchronous condition) lead to schizophrenia-like symptoms, such as increased source memory misattribution and subjective sense of reduced thought agency (Study 1), as well as increased subjective (Study 2) and behavioural indices of thought insertion (Study 3). These findings are interpreted within the framework of predictive coding theory and provide a link between aberrant predictive signalling mechanisms, impairments in action-monitoring, and delusional experiences of thought insertion.

3 PERSONAL CONTRIBUTIONS

Part 1

3.1 THOSE ARE YOUR LEGS: THE EFFECT OF VISUO-SPATIAL VIEWPOINT ON VISUO-TACTILE INTEGRATION AND BODY OWNERSHIP

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Those are Your Legs: The Effect of Visuo-Spatial Viewpoint on Visuo-Tactile Integration and Body Ownership

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Experiencing a body part as one's own, i.e., body ownership, depends on the integration of multisensory bodily signals (including visual, tactile, and proprioceptive information) with the visual top-down signals from peripersonal space. Although it has been shown that the visuo-spatial viewpoint from where the body is seen is an important visual top-down factor for body ownership, different studies have reported diverging results. Furthermore, the role of visuo-spatial viewpoint (sometime also called first-person perspective) has only been studied for hands or the whole body, but not for the lower limbs. We thus investigated whether and how leg visuo-tactile integration and leg ownership depended on the visuo-spatial viewpoint from which the legs were seen and the anatomical similarity of the visual leg stimuli. Using a virtual leg illusion, we tested the strength of visuo-tactile integration of leg stimuli using the crossmodal congruency effect (CCE) as well as the subjective sense of leg ownership (assessed by a questionnaire). Fifteen participants viewed virtual legs or non-corporeal control objects, presented either from their habitual first-person viewpoint or from a viewpoint that was rotated by 90° (third-person viewpoint), while applying visuo-tactile stroking between the participants legs and the virtual legs shown on a head-mounted display. The data show that the first-person visuo-spatial viewpoint significantly boosts the visuo-tactile integration as well as the sense of leg ownership. Moreover, the viewpoint-dependent increment of the visuo-tactile integration was only found in the conditions when participants viewed the virtual legs (absent for control objects). These results confirm the importance of first person visuo-spatial viewpoint for the integration of visuo-tactile stimuli and extend findings from the upper extremity and the trunk to visuo-tactile integration and ownership for the legs.

Keywords: crossmodal congruency effect, visuo-spatial viewpoint, body ownership, body illusion, legs

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INTRODUCTION

The experience of the body as one's own (i.e., the sense of body ownership), and its location in space, critically depend on multisensory and sensorimotor integration of bodily signals (Gallagher, 2000; Jeannerod, 2003; Blanke and Metzinger, 2009; Longo et al., 2010; Tsakiris, 2010; Blanke, 2012). The multisensory representation of one's body and its parts as well as body ownership are based on the integration and weighting of different sensory bodily inputs (proprioceptive, tactile, visual, auditory, vestibular, and visceral) according to spatio-temporal laws of multisensory bodily perception (Macaluso and Maravita, 2010; Blanke, 2012; Apps and Tsakiris, 2014; Samad et al., 2015). These bottom-up multisensory and motor signals are further integrated and compared with more stable, offline body representations, such as perceptual, conceptual and semantic knowledge of the body (Carruthers, 2008; de Vignemont, 2010; Longo et al., 2010; Serino and Haggard, 2010), as well as visual top-down signals about the form and position of the body (Blanke et al., 2015).

The sense of body ownership may fail in various neurological conditions producing erroneous and disturbed body perceptions, for example disownership of one's hand in somatoparaphrenia (Vallar and Ronchi, 2009; Romano et al., 2014), ownership for supernumerary limbs (Halligan et al., 1993; Guterstam et al., 2011) or seeing one's body from a third-person viewpoint as in out-of-body experiences (Blanke et al., 2002, 2004; Blanke and Arzy, 2005; Blanke and Mohr, 2005; Bunning and Blanke, 2005). Moreover, presenting conflicting multisensory information about the location and appearance of one's body or body part can experimentally modify the sense of body ownership. For example, in the rubber hand illusion participants see a rubber hand while their real hand is hidden from view. When both, the rubber and real hands are stroked in synchrony, the visual information usually biases proprioceptive signals resulting in illusory ownership for the rubber hand and in the experience of illusory touch, that is the perception of feeling touch as arising from the rubber hand (Botvinick and Cohen, 1998). Successful induction of bodily illusion through multisensory conflicts have been shown at the level of fingers (Dieguez et al., 2009), hands (Rubber hand illusion: Botvinick and Cohen, 1998), feet (Lenggenhager et al., 2015) or an entire body (Full body illusion: Ehrsson, 2007; Lenggenhager et al., 2007).

It has been argued that in order to experience body ownership, this multisensory body representation needs to be coded in a common, egocentric reference frame, characterized by seeing the body from a first-person visuo-spatial viewpoint (Blanke et al., 2002; Petkova and Ehrsson, 2008; Blanke and Metzinger, 2009). Several studies have shown that illusory ownership over a rubber hand is strongest when the rubber hand is seen close to the body (Lloyd, 2007) and from a first-person viewpoint that is at an anatomically plausible position (Ehrsson et al., 2004; Tsakiris and Haggard, 2005; Costantini and Haggard, 2007; Guterstam et al., 2011). Conversely, an induction of the RHI was achieved also in the absence of a first-person viewpoint, when tactile stimulation of the rubber hand was only seen in a mirror (Bertamini et al., 2011). Similarly, seeing another person's face (third-person viewpoint) being touched in synchrony with one's own face, leads to an enfacement illusion, evoking changes in the mental representation of one's own face (Tsakiris, 2008; Sforza et al., 2010; Tajadura-Jimenez et al., 2012). The effect of visuo-spatial viewpoint on whole body ownership has also been investigated by testing the effects of different viewpoints from which a body (Petkova et al., 2011; Pfeiffer et al., 2014) is seen. Several studies found that body ownership is stronger from first-person visuo-spatial viewpoints as compared to shifted or rotated viewpoints (Petkova and Ehrsson, 2008; Slater et al., 2010; Petkova et al., 2011; Maselli and Slater, 2013). Moreover, it has been shown that illusory ownership for a virtual body can also be induced when the virtual body is visually presented from a posterior third-person viewpoint (Lenggenhager et al., 2007; Aspell et al., 2009, 2013), but that additional third-person viewpoint changes did not modulate ownership for a virtual body (Pfeiffer et al., 2014). Also, the fact that in the evoked or spontaneous cases of out-of-body experiences people experience seeing their own body from a third-person point of view, despite reporting strong body ownership at the elevated and disembodied position (Blanke et al., 2002, 2004; Blanke and Mohr, 2005; Aspell et al., 2013), demonstrates that the relation between bodily self-consciousness (including body ownership) and the first-person visuo-spatial viewpoint is more complex than previously assumed.

Besides the visuo-spatial viewpoint, other factors have been shown to significantly affect the strength of bodily illusions. For example, ownership illusions decrease with longer delays between the visual and tactile stimulation and larger spatial separations of the visual and proprioceptive information about the hand location (Ehrsson et al., 2004; Costantini and Haggard, 2007; Lloyd, 2007), which is in line with temporal and spatial principles of multisensory integration (Holmes and Spence, 2005; Stein and Stanford, 2008). The illusion is also reduced with decreased anatomical resemblance of the stroked hand (normally in the form of different objects) with respect to the participants' real hand (Haans et al., 2008; Tsakiris et al., 2010) or incongruent hand laterality (Tsakiris and Haggard, 2005), indicating the involvement of visual top-down modulation in the process of embodiment of the rubber hand.

The most commonly used measures to assess subjective experience of illusory ownership of body parts or of a whole body are questionnaire ratings (Botvinick and Cohen, 1998; Tsakiris and Haggard, 2005; Lenggenhager et al., 2007). Objective, reaction-time based evidence has been obtained by using the crossmodal congruency effect (CCE) task (Spence et al., 1998), in which participants are asked to respond to tactile stimuli applied to their body while ignoring visual distractor stimuli, which may occur at a congruent or an incongruent location with respect to the tactile (target) stimulus. The CCE has been previously used as an implicit measure of body ownership, showing that the CCE is associated with a self-attribution of an artificial hand (Pavani et al., 2000; Zopf et al., 2010) or virtual body (Aspell et al., 2009; Maselli and Slater, 2014).

Research on body ownership and bodily processing in general has mostly concentrated on hands (see Tsakiris, 2010, for a review) or body (see Blanke, 2012, for a review), and only few studies have investigated how the lower body is represented in the brain and whether this representation is different from the one of the hand (Schicke and Röder, 2006; Heed and Röder, 2008; Schicke et al., 2009; van Elk et al., 2013). In fact, there are numerous functional differences between upper and lower limbs, compatible with neural differences in body ownership mechanisms; in comparison to lower limbs, the hands are more frequently and with different complexity used for action and object manipulations; they have more degrees of freedom to move, can be positioned in a much wider portion of the peripersonal space, and frequently interact with other parts of the body. On contrary, the functional role of the legs mostly pertains to locomotion, and the range of their possible positions in space is smaller and is mostly restricted to the sagittal vertical plane of the body. As a consequence, the integration of multisensory stimuli related to the feet and surrounding space might differ from what is described for the hands (van Elk et al., 2013). While hand actions require hand-centered representation, locomotive actions require a representation that is foot-centered and centered on the body midline (Morton and Bastian, 2004; Kannape et al., 2010; Kannape and Blanke, 2013; Galli et al., 2015), suggesting that space and body are represented differently during manual and pedal actions. However, studies, which directly compared visuo-tactile integration of stimuli related to hands and feet, yielded inconclusive results. For example, it was shown that the multisensory representation of the feet does not differ from that of the hands as inferred from measures of multisensory integration such as the CCE or temporal order judgment tasks (Schicke and Röder, 2006; Schicke et al., 2009). However, another study confirmed that the magnitude of the CCE did not differ between hands and feet, but only when they were in an anatomical, uncrossed position, indicating a similar peripersonal space representation (van Elk et al., 2013). However, when the limbs were crossed, only hand CCEs were affected, but not feet CCEs, pointing to a difference between hands and feet in the integration of visual, tactile and proprioceptive signals.

In the present study we investigated whether visuo-tactile integration for leg stimuli (assessed by the CCE) and leg ownership depend on the visuo-spatial viewpoint and the anatomical similarity of the legs' shape. In a virtual leg illusion, virtual legs were visually presented to the participants on a head-mounted display (HMD), so that they saw virtual legs as superimposed over their physical legs. The virtual legs were either shown from the participant's habitual first-person viewpoint, or as rotated by 90°, to simulate a third-person viewpoint. To induce ownership for the virtual legs we followed the established protocol of visuo-tactile stimulation as for the rubber hand. Visuo-tactile stroking was applied either at a virtual legs or a virtual control object not resembling human legs (Pavani et al., 2000; Tsakiris and Haggard, 2005; Lenggenhager et al., 2007; Aspell et al., 2009, 2013; Salomon et al., 2012). We predicted that seeing legs in first-person viewpoint would result in stronger body ownership and higher CCE score as compared to the conditions where the legs are seen from the third-person viewpoint or where, instead of legs, wooden blocks are presented.

MATERIALS AND METHODS

Participants

Nineteen right-handed healthy participants from the student population at Ecole Polytechnique Fédérale de Lausanne (EPFL) took part in the experiment (5 females, mean age 25.8 ± 3.8 years, range 18–33 years). All participants had normal or corrected-to normal sight and no psychiatric or neurological history. Their participation in the study was reimbursed (20 CHF). They had no previous experiences with the task or experimental paradigm. All participants gave written informed consent; the study was approved by the ethics committee of EPFL and was performed in accordance with the Declaration of Helsinki. The data of four participants were not included in the analysis due to a technical problem (two participants) and due to the below-chance performance at the CCE task (two participants).

Virtual Leg Illusion Paradigm

The virtual leg illusion paradigm was adapted from the rubber hand illusion (Botvinick and Cohen, 1998) and full body illusion paradigms (Ehrsson, 2007; Lenggenhager et al., 2007; Petkova and Ehrsson, 2008) to study the role of visuo-spatial viewpoint in the embodiment of lower limbs. Subjects were comfortably sitting in a chair wearing a HMD (HMD, V-Real Viewer 3D SVGA, 800 × 600 pixels image resolution, 35° field of view, VRealities). The virtual legs or wooden objects were placed on another chair, mimicking a usual sitting position. A video camera recorded the virtual legs or wooden objects from a height and angle that corresponded to a subjective first person viewpoint and the video was projected in real time (except for asynchronous blocks, see below) onto the HMD. Thus, the subjects viewed the virtual legs or wooden objects as superimposed over their real legs (they were instructed to look in the direction of their legs). White noise was presented over headphones to mask the noise from the vibrators and surrounding. To induce the virtual leg illusion, the experimenter irregularly tapped (on average 2 taps per second) the participant's left leg (dorsal surface between the knee and hip) and the corresponding virtual leg with a wooden stick. The subjects therefore viewed the virtual leg or wooden objects being tapped via the HMD and feel the touch applied to their real leg. Simultaneous tactile stimulation of the left and right leg would be preferred during illusion induction, however, due to the limitation of the manual application of tapping, only lateralized leg stimulation was possible.

In the synchronous conditions the "seen tapping" and "felt tapping" matched spatially and temporally, whereas in the asynchronous blocks the visual information was delayed for 500 ms (using a video delaying device). The visuo-spatial viewpoint was manipulated by presenting subjects with the virtual legs (or wooden objects) in their habitual first-person viewpoint or in a third-person viewpoint, where the video image of the virtual legs (or wooden objects) was rotated by 90° anticlockwise. Each phase of illusion induction lasted for 60 s. The virtual leg illusion paradigm is shown in **Figure 1**.

Crossmodal Congruency Effect Task

In order to study the role of visuo-spatial perspective in the embodiment of virtual legs or wooden objects, we adapted a behavioral task known as *Crossmodal distractor congruency task* by Spence et al. (1998). In this task participants are asked to make speeded judgments about the position of a tactile stimulus applied to their body, while ignoring visual distractor stimulus occurring at the spatially congruent or at an incongruent location with respect to the tactile (target)

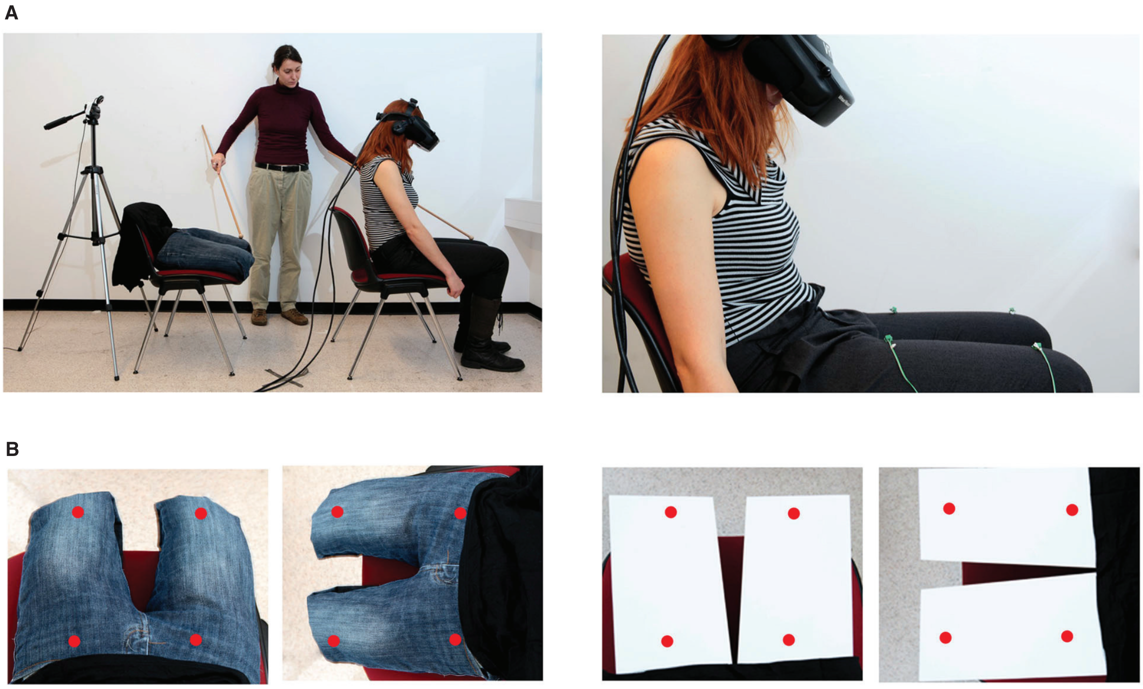

FIGURE 1 | Experimental setup. (A) (LEFT) Virtual leg illusion. The experimenter simultaneously applies tactile stimuli to the participant's leg and to the filmed virtual legs or wooden objects using a wooden stick. **(A)** RIGHT The participant wears a head-mounted display onto which the real-time (delayed in asynchronous condition) video of the virtual legs or wooden objects is projected. Four vibrating devices are attached to the participant's legs. **(B)** (LEFT) The virtual legs or wooden objects as seen by the participant through the head-mounted display, presented in first- or third-person viewpoint. The red dots represent the positions of vibrotactile stimuli and visual distractors during the crossmodal congruency task. In the congruent conditions the vibrotactile stimulus and visual distractor appeared at the same location, whereas in the incongruent conditions they appeared at the same side but at a different position.

stimulus. The responses are usually slowed down when the distractor appears at an incongruent location. The reaction time (RT) difference between the incongruent and congruent trials is defined as CCE. The task has been extensively used to investigate multisensory integration in relation with peripersonal space and body representation as the CCE is larger when the visual distractors appear closer to the tactile (target) cue (Spence et al., 1998, 2004) or when the visual distractors are presented on a body part or whole body, which visually resemble a real human body (Pavani et al., 2000; Austen et al., 2004; Aspell et al., 2009). Thus, the task has been as such used as an implicit measure of hand (Pavani et al., 2000; Pavani and Castiello, 2004; Spence et al., 2004; Shore et al., 2006; Igarashi et al., 2010) and body ownership (Aspell et al., 2009; Maselli and Slater, 2014).

In the present study the vibrotactile stimuli were delivered by four vibration devices, each consisting of a small vibrating motor [Precision MicroDrives shaftless vibration motors, model 312–101, 3V, 60 mA, 9000 rpm (150 Hz), 5 g]. The motors had a surface area (the area touching the participant's leg) of 113 mm^2. The activation of the motors gave a clearly perceived and easy-to-localize stimulation. Two devices were attached to each of the participants' legs using a medical tape: on each leg, the "upper" device was positioned approximately 3 cm from the knee and the "lower" device 25 cm below (**Figure 1**). The visual distractors were displayed through the HMD as a red dot at four different positions corresponding to the location of the vibrotactile motors. Vibro-tactile and visual distractors were presented simultaneously for 35 ms (stimuli onset was synchronous). In the congruent trials, the visual distractor appeared as superimposed to the activated vibrotactile stimulator (same position), whereas in the incongruent trials the visual distractor appeared at the opposite elevation, on the same side (same leg) according to the participant egocentric reference frame. The locations of appeared vibrotactile stimuli and visual distractors were balanced and randomized. The task in each experimental condition consisted of 96 trials (48 congruent and 48 incongruent; 48 were delivered with upper vibrotactile motors and 48 with lower; 48 on the right and 48 on the left leg). Stimulus timings were controlled by a program written with ExpyVR, a custom-built multimedia stimuli presentation software, developed with Python 2.6 and the Open Graphics Library v.2.2 (http://lnco.epfl.ch/).

The subjects were instructed to direct their gaze toward their real legs and fixate on the middle of the video conveyed through HMD. They were asked to make speeded judgments of whether they felt the vibrotactile stimulus at upper (knee level) or lower (hip level) position on their legs (with respect to their

TABLE 1 | Virtual leg illusion questionnaire.

	Item	Label
1	I had the impression that the legs/objects I was looking at were my real legs.	Ownership
2	I had the impression that the touch I saw was applied to my legs.	Illusory touch
3	I had the impression of being able to move the legs/objects.	Illusion of motor agency
4	I had the impression that my legs had changed position.	Illusion of proprioceptive rotation

The questionnaire included the four statements shown, describing illusory ownership, illusory touch, illusion of motor agency and illusion of proprioceptive leg rotation, which served as a control question for suggestibility. Participants indicated their response on a seven-point Likert scale ranging from "completely agree" (+++) to "completely disagree" (− − −).

anatomical reference frame), regardless of the leg laterality, while ignoring the visual distractors. They responded by pressing one of two buttons on a keypad with their right hand. After the stimuli presentation, the participants had 2000 ms to respond to the tactile target with a button press before the next trial commenced.

Virtual Leg Illusion Questionnaire

To assess the subjective experience of sense of ownership over the virtual legs or wooden objects, the participants were asked to rate 4 items from a questionnaire designed to capture the leg illusion, which was adapted from the rubber hand illusion (Botvinick and Cohen, 1998) and full body illusion (Ehrsson, 2007; Lenggenhager et al., 2007) questionnaires. The items referred to the sense of leg ownership, illusory touch, sense of motor agency over the displayed virtual legs or wooden objects, and illusion of proprioceptive leg rotation. We hypothesized that the sense of illusory ownership, illusory touch and illusion of motor agency would be stronger in the condition with synchronous visuo-tactile stimulation of the virtual legs shown in first-person viewpoint. On the other hand, the illusion of proprioceptive leg rotation should be stronger in the synchronous condition where the virtual legs are presented rotated, in the third-person viewpoint. The questionnaire items are presented in **Table 1**. Participants rated to which degree they agree with the item statement on a 7-item Likert scale ranging from −3 ("completely disagree") to +3 ("completely agree").

Experimental Design

In a 2 × 2 × 2 repeated measures design we manipulated *Synchrony* of administered visuo-tactile tapping (Synchronous, Asynchronous), *Visuo-spatial viewpoint* (first-person, third-person), and *Body similarity* (virtual legs, wooden objects), thus in total encompassing 8 conditions. Each condition consisted of two illusion induction phases, where the experimenter applied visuo-tactile tapping to the participant's leg and the virtual leg/wooden object for 60 s. Each illusion induction phase was followed by the CCE task (48 trials). The effects of the experimental manipulations on multisensory integration mechanisms were measured with the CCE scores on RT (see below) and error rate (ER). The subjective experience of embodiment was assessed with a questionnaire administered at the end of each condition.

Procedure

The participants were first informed about the procedure of the experiment and asked to sign an informed consent to participate. While seated in a chair and wearing an HMD, the experimenter attached the vibro-tactile motors to the participant's legs and aligned the video frame of the virtual legs or wooden objects to best fit the position of the vibro-tactile motors and the participant's point of view. Then the participants were instructed about the CCE task and underwent a short training session, where the visual distractors were displayed on a black screen (16 trials). The experimental procedure was identical for all eight conditions. Subjects were instructed to orient their gaze in the direction of their legs, keep their eyes open and fixate on a location in the middle of the screen, as viewed via the HMD. Each condition consisted of two illusion-induction phases and two CCE task blocks (see the Experimental design section above). At the end of the condition the subjects removed the HMD and filled out the Illusion questionnaire. They were encouraged to take a short break before the subsequent block. The order of the conditions was randomized across the subjects.

Data Analysis

The dependent measures of the experimental manipulations used for the data analyses were RT CCE scores, ER CCE and questionnaire ratings.

Crossmodal congruency effect scores were calculated by subtracting the mean RT (or ER) in congruent trials from the mean RT (or ER) in incongruent trials. Trials with incorrect responses and trials in which subjects failed to respond within 2000 ms were discarded from the RT analysis (on average, 2.3 % of trials), whereas the ER was calculated as the percentage of incorrect responses for all the valid trials (excluding only the trials with a failed response within 2000 ms). CCE scores were analyzed using repeated measures ANOVA with three within-subject factors: *Synchrony* (synchronous/asynchronous), *Visuo-spatial viewpoint* (first-person/third-person), and *Body similarity* (virtual legs/wooden objects). In the presentation and interpretation of RTs, we have mainly focused on the CCE scores from RT data rather than ER, as the RT CCE has been shown to be more sensitive (Pavani et al., 2000; Austen et al., 2004; Shore et al., 2006), however, we also report the ER in **Table 2**, and the ER CCE analyses.

Due to the ordinal type of the questionnaire data, the questionnaire scores were first ipsatized (Fischer and Milfont, 2010), and then analyzed with repeated measures ANOVA, using the same three within-subject factors as for the CCE task data. The significance (alpha) level used was 0.05. Significant interactions were followed up with planned pairwise comparisons using two-tailed paired *t*-tests. The alpha level of significance was adjusted accordingly to the number of comparisons using the Bonferroni method.

Pearson product-moment correlation coefficients were calculated to assess the relationship between the questionnaire ratings and CCE score.

TABLE 2 | Crossmodal congruency task results.

	Synchronous		Asynchronous	
	Congruent	Incongruent	Congruent	Incongruent
REACTION TIMES				
LEGS				
1 POV	1220 (41)	1320 (49)	1200 (36)	1302 (43)
3 POV	1219 (42)	1234 (46)	1222 (36)	1246 (40)
OBJECT				
1 POV	1148 (40)	1215 (47)	1151 (40)	1216 (43)
3 POV	1170 (43)	1200 (41)	1166 (33)	1201 (40)
ERROR RATES				
LEGS				
1 POV	0.04 (0.01)	0.08 (0.02)	0.02 (0.01)	0.07 (0.01)
3 POV	0.04 (0.01)	0.04 (0.01)	0.03 (0.01)	0.06 (0.01)
OBJECT				
1 POV	0.03 (0.01)	0.04 (0.01)	0.01 (0.00)	0.05 (0.01)
3 POV	0.04 (0.01)	0.05 (0.02)	0.03 (0.01)	0.04 (0.01)

Average reaction times (in milliseconds, upper panel) and error rates (in percentages, lower panel) for virtual legs and wooden objects. Standard errors of the mean are shown in brackets. 1 POV, First-person viewpoint; 3 POV, Third-person viewpoint; LEGS, Virtual legs; OBJECT, Wooden objects.

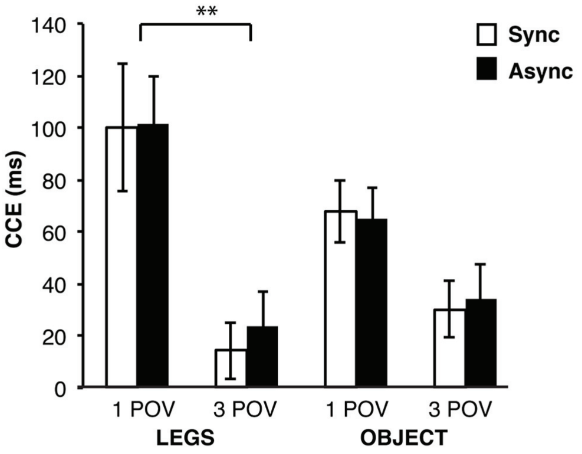

FIGURE 2 | CCE results. The visuo-tactile integration was the strongest in the conditions where participants saw the virtual legs in the first-person viewpoint and significantly differed from the conditions when they saw the virtual legs in the third-person viewpoint, whereas the visuo-spatial viewpoint did not significantly affect the visuo-tactile integration when participants were seeing the wooden objects. The error bars depict the standard error of the mean. Sync, Synchronous; Async, Asynchronous; 1 POV, First-person viewpoint; 3 POV, Third-person viewpoint; LEGS, Virtual legs; OBJECT, Wooden objects. $^{**}p < 0.01$.

RESULTS

Crossmodal Congruency Effect. Reaction Times

The three-way repeated measures ANOVA on RT CCE showed a significant main effect of Visuo-spatial viewpoint [$F(1,14) = 32.75$, $p < 0.001$, $\eta_p^2 = 0.70$]: the CCE magnitude was larger when the viewed legs or control object were seen from the first-person viewpoint ($M = 83.7$ ms, SEM = 13.0 ms) than seen from the third-person viewpoint ($M = 25.6$ ms, SEM = 9.4 ms). Not significant were the main effects of Synchrony [$F(1,14) = 0.25$, $p = 0.626$, $\eta_p^2 = 0.02$] and Body similarity [$F(1,14) = 1.70$, $p = 0.214$, $\eta_p^2 = 0.11$]. Significant was the two-way interaction between the Visuo-spatial viewpoint and Body similarity [$F(1,14) = 5.63$, $p = 0.033$; $\eta_p^2 = 0.29$]. *Post hoc* analysis of this interaction showed a larger CCE in the first-person viewpoint as compared to the third-person viewpoint condition, but only when the participants viewed virtual legs [first-person viewpoint: $M = 101.9$ ms, SEM = 19.4 ms, third-person viewpoint: $M = 19.2$ ms, SEM = 10.6 ms; $t(14) = 5.17$, $p < 0.001$, $\alpha(\text{corr}) = 0.0125$], and not when they viewed the control objects [first-person viewpoint: $M = 66.5$ ms, SEM = 9.2 ms, third-person viewpoint: $M = 32.1$ ms, SEM = 10.6 ms; $t(14) = 2.76$, $p = 0.015$, $\alpha(\text{corr}) = 0.0125$]. The other two pairwise comparisons did not reach the level of significance after correction for multiple comparisons: no significant differences in the CCE were found between legs or objects when they were viewed in the first-person viewpoint [$t(14) = 2.20$, $p = 0.044$, $\alpha(\text{corr}) = 0.0125$] or when they were viewed in the third-person viewpoint [$t(14) = -1.34$, $p = 0.203$, $\alpha(\text{corr}) = 0.0125$]. Non-significant were the two-way interactions between Synchrony and Body similarity [$F(1,14) = 0.17$, $p = 0.690$, $\eta_p^2 = 0.01$] and between Synchrony and Visuo-spatial viewpoint [$F(1,14) = 0.16$, $p = 0.695$, $\eta_p^2 = 0.01$]. The three-way interaction was also not significant [$F(1,14) < 0.01$, $p = 0.956$, $\eta_p^2 < 0.01$]. The mean RTs for each condition are shown in **Table 2**. The CCE RTs are shown in **Figure 2**.

Crossmodal Congruency Effect. Error Rates

The three-way repeated measures ANOVA on ER CCE scores showed a significant main effect of Visuo-spatial viewpoint [$F(1,14) = 6.54$, $p = 0.023$, $\eta_p^2 = 0.32$], where regardless of the synchrony of stroking, seeing the virtual legs or control objects in the first-person viewpoint ($M = 0.3$, SEM < 0.1) led to higher ER CCE scores than seeing them in the third-person viewpoint ($M = 0.1$, SEM < 0.1). Not significant were the main effects of Synchrony [$F(1,14) = 2.33$, $p = 0.149$. $\eta_p^2 = 0.14$] and Body similarity [$F(1,14) = 1.53$, $p = 0.237$, $\eta_p^2 = 0.10$]. Not significant were the two-way interactions between Synchrony and Visuo-spatial viewpoint [$F(1,14) = 0.07$, $p = 0.790$, $\eta_p^2 = 0.01$], between Synchrony and Body similarity [$F(1,14) = 0.66$, $p = 0.429$, $\eta_p^2 = 0.05$] and between Visuospatial viewpoint and Body similarity [$F(1,14) = 1.96$, $p = 0.183$, $\eta_p^2 = 0.12$]. The three-way interaction between all three experimental factors was also not significant [$F(1,14) = 2.30$, $p = 0.152$, $\eta_p^2 = 0.14$]. The mean ERs are shown in **Table 2**.

Questionnaire Ratings

Ownership

The questionnaire item: "*I had the impression that the legs/objects I was looking at were my real legs*." was used to assess the degree of body ownership over the displayed virtual legs/wooden objects. Data analysis of the item ratings revealed a significant main effect of Synchrony [$F(1,14) = 6.39$, $p = 0.024$, $\eta_p^2 = 0.31$], showing that illusory ownership was experienced more strongly when the visuo-tactile stimulation was synchronous ($M = 0.2$, SEM = 0.1), as compared to asynchronous ($M = -0.2$, SEM = 0.1). Significant were also the main effects of Visuo-spatial viewpoint [$F(1,14) = 9.70$, $p = 0.008$, $\eta_p^2 = 0.41$] and Body similarity [$F(1,14) = 18.63$, $p = 0.001$, $\eta_p^2 = 0.57$]. Thus, the sense of ownership was stronger when the legs/objects were seen from the first-person viewpoint ($M = 0.3$, SEM = 0.1), as compared to the third-person viewpoint ($M = -0.3$, SEM = 0.1), and when the participants saw the virtual legs ($M = 0.6$, SEM = 0.3) as compared to the control objects ($M = -0.6$, SEM = 0.3). Not significant were the two-way interaction effects between Synchrony and Visuo-spatial viewpoint [$F(1,14) = 0.52$, $p = 0.482$, $\eta_p^2 = 0.04$], between Synchrony and Body similarity [$F(1,14) = 0.62$, $p = 0.446$, $\eta_p^2 = 0.04$], and between Visuo-spatial viewpoint and Body similarity [$F(1,14) = 3.14$, $p = 0.098$, $\eta_p^2 = 0.18$]. The three-way interaction was also not significant [$F(1,14) = 0.80$, $p = 0.387$, $\eta_p^2 = 0.05$].

Illusory Touch

In order to assess the strength of experienced illusory touch during the visuo-tactile stimulation, the participants rated the questionnaire item: "*I had the impression that the touch I saw was applied to my legs.*" The data analysis showed significant main effects of Synchrony [$F(1,14) = 23.39$, $p < 0.001$, $\eta_p^2 = 0.62$], Visuo-spatial viewpoint [$F(1,14) = 4.89$, $p = 0.044$, $\eta_p^2 = 0.26$], and Body similarity [$F(1,14) = 4.73$, $p = 0.047$, $\eta_p^2 = 0.25$]. Thus, the experience of illusory touch was reported stronger when the visuo-tactile stimulation was synchronous ($M = 1.0$, SEM = 0.1), as compared to asynchronous ($M = 0.2$, SEM = 0.1). The intensity of the illusory touch was also larger when the legs or objects were presented in the participant's first-person viewpoint ($M = 0.5$, SEM = 0.1), than when seen from the third-person viewpoint ($M = 0.3$, SEM = 0.1), and when the subjects saw the virtual legs ($M = 0.6$, SEM = 0.1) as compared to when they saw the objects ($M = 0.2$, SEM = 0.1). Not significant were the two-way interaction effects between Synchrony and Visuo-spatial viewpoint [$F(1,14) = 0.51$, $p = 0.487$, $\eta_p^2 = 0.04$], between Synchrony and Body similarity [$F(1,14) = 0.15$, p = 0.708, $\eta_p^2 = 0.01$], and between Visuo-spatial viewpoint and Body similarity [$F(1,14) = 0.17$, $p = 0.688$, $\eta_p^2 = 0.01$]. The interaction between the three experimental factors was also not significant [$F(1,14) = 0.36$, p = 0.559, $\eta_p^2 = 0.03$].

Illusion of Agency

As the sense of embodiment also comprises of the sense of being in control of a body or a body part, we asked participant to report the strength of experienced sense of motor agency by rating the questionnaire item: "*I had the impression of being able to move the virtual legs/objects.*" The analysis of the item ratings showed a significant main effect of Synchrony [synchronous: $M = 0.0$, SEM = 0.1; asynchronous: $M = -0.4$, SEM = 0.1; $F(1,14) = 14.90$, $p = 0.002$, $\eta_p^2 = 0.52$], Visuo-spatial viewpoint [first-person viewpoint: $M = 0.0$, SEM = 0.1; third-person viewpoint: $M = -0.3$, SEM = 0.1; $F(1,14) = 6.17$, $p = 0.026$, $\eta_p^2 = 0.31$] and Body similarity [legs: $M = 0.1$, SEM = 0.1; objects: -0.5, SEM = 0.1; $F(1,14) = 13.52$, $p = 0.002$, $\eta_p^2 = 0.49$]. Significant was the two-way interaction between Synchrony and Visuo-spatial viewpoint [$F(1,14) = 6.84$, $p = 0.020$, $\eta_p^2 = 0.33$], but not between Synchrony and Body similarity [$F(1,14) = 0.01$, $p = 0.934$, $\eta_p^2 < 0.01$] or between Body similarity and Visuo-spatial viewpoint [$F(1,14) = 2.14$, $p = 0.165$, $\eta_p^2 = 0.13$]. We have found a significant three-way interaction between Body similarity, Visuo-spatial viewpoint and Synchrony [$F(1,14) = 6.10$, $p = 0.027$, $\eta_p^2 = 0.30$]. The *post hoc* analysis of the interaction effect revealed only one significant pairwise comparison, showing that the sense of motor agency was stronger when the participants were seeing objects in the first-person viewpoint during synchronous visuo-tactile stimulation ($M = -0.1$, SEM = 0.2), as compared to seeing them during asynchronous stimulation [$M = -0.8$, SEM = 0.2; $t(14) = 3.87$, $p = 0.002$, $\alpha(\text{corr}) = 0.008$], although the average ratings in both conditions were low. Other pairwise comparisons did not reach the level of significance after the correction for multiple comparisons, adjusted at $\alpha(\text{corr}) = \alpha/6 = 0.008$ [Legs-1POV-Sync/Legs-1POV-Async: $t(14) = 1.78$, $p = 0.096$; Legs-1POV-Sync/Legs-3POV-Sync: $t(14) = 2.00$, $p = 0.066$; Legs-1POV-Sync/Objects-1POV-Sync: $t(14) = 2.79$, $p = 0.014$; Legs-3POV-Sync/Objects-3POV-Sync: $t(14) = 1.97$, $p = 0.069$; Objects-1POV-Sync/Objects-3POV-Sync: $t(14) = 2.04$, $p = 0.060$].

Illusion of Proprioceptive Leg Rotation

In order to assess the subjective changes in proprioceptive sense of participant's legs position due to the manipulation of viewpoint we used the questionnaire item: "*I had impression that my legs had changed position.*"

The analysis of the item ratings revealed that the main effect of Synchrony was not significant [synchronous: $M = -0.2$, SEM = 0.1; asynchronous: $M = -0.3$, SEM = 0.1; $F(1,14) = 2.25$, $p = 0.156$, $\eta_p^2 = 0.14$]. Significant where the main effects of Visuo-spatial viewpoint [first-person viewpoint: $M = -0.5$, SEM = 0.1; third-person viewpoint: $M = 0.0$, SEM = 0.2; $F(1,14) = 5.19$, $p = 0.039$, $\eta_p^2 = 0.27$] and Body similarity [legs: $M = 0.2$, SEM = 0.2; objects: $M = -0.6$, SEM = 0.1; $F(1,14) = 11.34$, $p = 0.005$, $\eta_p^2 = 0.45$]. We found a significant two-way interaction between Synchrony and Visuo-spatial viewpoint [$F(1,14) = 17.88$, $p = 0.001$, $\eta_p^2 = 0.56$]. Further *post hoc* analysis of the interaction effect showed that the proprioceptive illusion of leg rotation was stronger during synchronous visuo-tactile stimulation, but only when the legs or objects were presented in the third-person viewpoint [synchronous: $M = 0.3$, SEM = 0.2; asynchronous: $M = -0.2$, SEM = 0.2; $t(14) = 3.71$, $p = 0.002$, $\alpha(\text{corr}) = 0.0125$] and not when seen in the first-person viewpoint [synchronous: $M = -0.6$, SEM = 0.1; asynchronous: $M = -0.4$; SEM = 0.1; $t(14) = 1.01$, $p = 0.332$, $\alpha(\text{corr}) = 0.0125$]. Seeing the legs or objects in the third-person viewpoint during synchronous visuo-tactile stimulation also resulted in stronger proprioceptive illusion than seeing them in the first-person viewpoint [$t(14) = 4.00$, $p = 0.001$, $\alpha(\text{corr}) = 0.0125$]. The differences in average ratings between first- and third-person viewpoint when legs or objects were seen during asynchronous stroking were not significant [$t(14) = -0.79$, $p = 0.445$]. Not significant were the two-way interactions between Synchrony and Body similarity

[$F(1,14) = 0.33$, $p = 0.575$, $\eta_p^2 = 0.02$] and between Visuo-spatial viewpoint and Body similarity [$F(1,14) = 0.82$, $p = 0.382$, $\eta_p^2 = 0.06$]. Not significant was also the three-way interaction between the experimental factors [$F(1,14) = 3.41$, $p = 0.086$, $\eta_p^2 = 0.20$].

Based on the prediction that the illusion of proprioceptive leg rotation should be stronger in the synchronous condition where the virtual legs are presented in the third-person viewpoint as compared to the first-person viewpoint, and thus result in different pattern of responding across conditions as compared to the other three questionnaire items, the ratings of this item were used as a control for a bias in responding to the other three questionnaire items due to suggestibility or social desirability. Thus, we compared the ratings of this item (Illusion of proprioceptive leg rotation) in the condition where the virtual legs were viewed from the first-person viewpoint during synchronous visuo-spatial stimulation with the ratings of other three questionnaire items (Illusory ownership, Illusory touch and Illusion of motor agency) of the same condition. The ratings of the *Illusion of proprioceptive leg rotation* item were significantly lower than the ratings of the *Illusory ownership* [two-tailed paired t-test: $t(14) = 5.83$, $p < 0.001$, $\alpha(\text{corr}) = 0.017$], *Illusory touch* [two-tailed paired t-test: $t(14) = 5.94$, $p < 0.001$, $\alpha(\text{corr}) = 0.017$] and *Illusion of motor agency* [two-tailed paired t-test: $t(14) = 3.00$, $p = 0.010$, $\alpha(\text{corr}) = 0.017$] of the same condition. The average ipsatized questionnaire ratings are shown in **Figure 3**.

Correlation Between CCE and Questionnaire Data

Pearson product-moment correlation coefficients were calculated to assess the relationship between the questionnaire ratings and CCE score. In particular, we correlated the ratings of the four questionnaire items of the condition where participants viewed the virtual legs from a first-person viewpoint during synchronous visuo-tactile stimulation with the CCE score obtained during the same condition. None of the correlation coefficients was statistically significant [Illusory ownership: $r(15) = 0.21$, $p = 0.450$; Illusory touch: $r(15) = 0.32$, $p = 0.238$; Illusion of motor agency: $r(15) = -0.05$, $p = 0.850$; Illusion of proprioceptive leg rotation: $r(15) = 0.36$, $p = 0.190$].

DISCUSSION

The present study investigated how visuo-tactile integration and leg ownership depend on the visuo-spatial viewpoint using the virtual leg illusion paradigm. The participants were viewing either legs or control objects from either a first-person or third person viewpoint on an HMD, while receiving synchronous or asynchronous visuo-tactile stimulation. The study revealed two major findings about the mechanisms of multisensory integration for stimuli from the lower limbs and the sense of leg ownership. First, the data show that the first-person visuo-spatial viewpoint enhances the sense of leg ownership and the interference of visual over tactile cues at the lower limbs. This finding further extends the important role of visual top-down factors, here the first-person viewpoint, to the integration of leg-related multisensory stimuli and leg ownership as previously shown for hands (Pavani et al., 2000; Zopf et al., 2010) and the full body (Petkova et al., 2011; Maselli and Slater, 2014). Second, we show that the viewpoint effect on the multisensory integration of stimuli from the lower limbs is stronger when legs are shown, as the CCE magnitude decreased for non-leg control objects.

Top-down Modulation of the Crossmodal Congruency Effect

The CCE RTs revealed the highest impact of visual distractors when the virtual legs were presented from the first-person viewpoint, indicating a stronger degree of visuo-tactile interference compared to third-person viewpoints and compared to the wooden blocks seen from the first-person viewpoint. Thus, the CCE, based on dominance of task-irrelevant visual stimuli over tactile stimuli, decreased when the legs were viewed in the third-person visuo-spatial viewpoint (also not differing in magnitude from the condition in which the blocks were presented in the third-person viewpoint). Similarly, the effect of visuo-spatial viewpoint on multisensory integration was also reflected in ERs, which decreased when the legs or objects were presented in the third-person viewpoint. The current findings show that visuo-tactile integration for the legs as quantified by the CCE does not only depend on the bottom-up, temporo-spatial visuo-tactile stimulation (e.g., prior visuo-tactile tapping), but also on two visual top-down factors: a pre-existing internal body representation (i.e., corporeal similarity of the virtual legs) and the visuo-spatial viewpoint.

The performance on the CCE task has been associated with the activity of multimodal neurons in premotor and posterior parietal regions, which respond to stimulation within their tactile receptive fields on the body as well as to visual stimuli appearing within the peripersonal space surrounding the given body part despite positional changes of the body part (Maravita et al., 2003; Macaluso and Maravita, 2010). As such it has been proposed that they process multisensory stimuli in a common body-centered (arm- or leg-centered) reference frame (Rizzolatti et al., 1997; Graziano and Gross, 1998; Graziano et al., 2000; Pouget et al., 2002; Avillac et al., 2005). It has been suggested that such body-part centered multisensory coding of stimuli, implemented in premotor and posterior parietal multimodal neurons do not only map the location of body parts in space (Lloyd et al., 2003), but are also fundamental in body ownership (Maravita et al., 2003; Ehrsson et al., 2004; Makin et al., 2007; Zopf et al., 2010; Blanke, 2012).

In our study, viewing the wooden objects in first-person viewpoint reduced the CCE amplitude as compared to viewing the virtual legs in the same viewpoint. Comparable results were also reported in a study with the full body illusion paradigm (Aspell et al., 2009, 2010), where seeing a body modulated the CCE but not when seeing a body-sized control object. We found that visuo-tactile integration as quantified by the CCE was further decreased when the legs or wooden blocks were presented in the rotated orientation, mimicking a third-person viewpoint (i.e., providing a visual reference frame that did not match the egocentric, somatotopic and proprioceptive) reference frame of the legs, compatible, with weakened visuo-tactile integration due to misalignment (i.e., the coordinates within which the visual

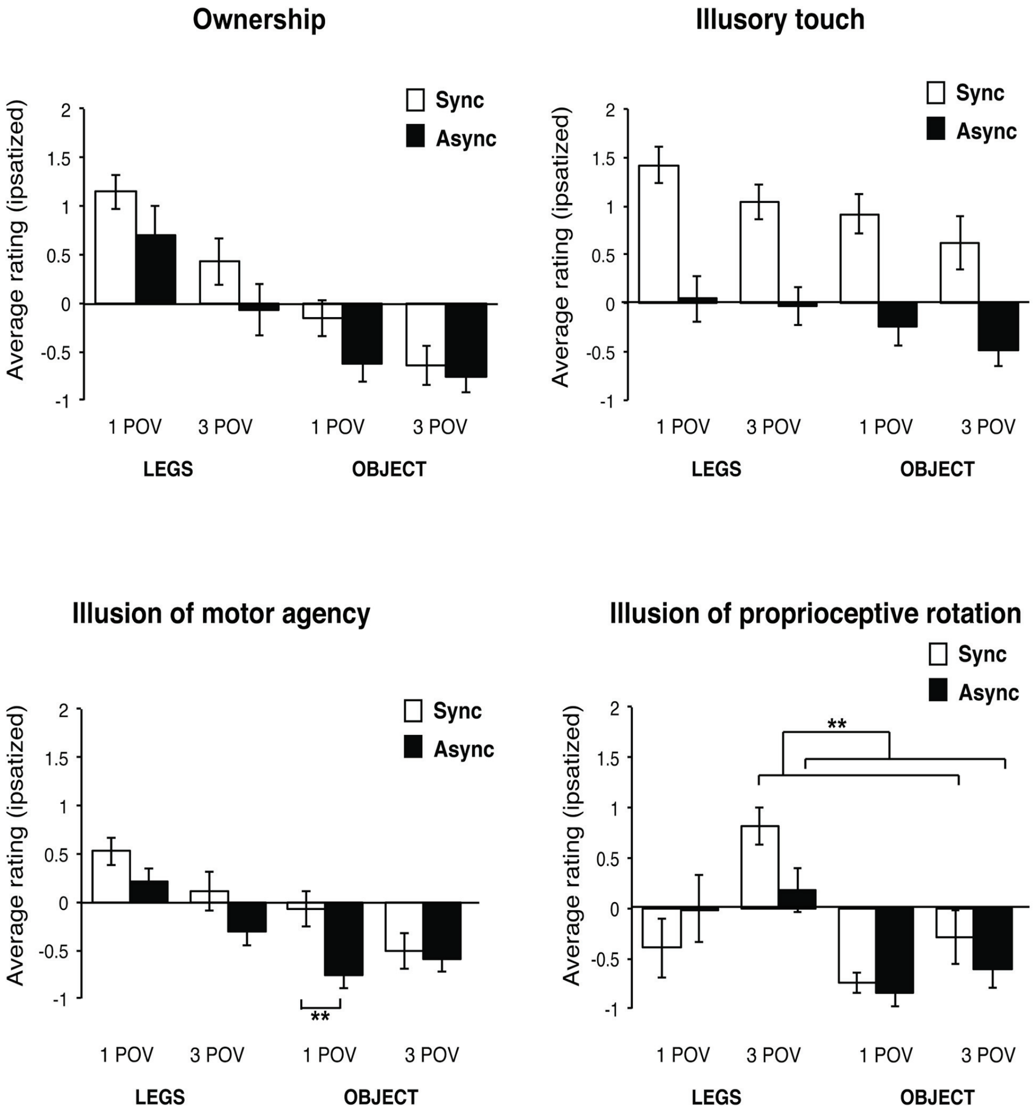

FIGURE 3 | Questionnaire results. The figure represents the average ipsatized ratings of the Virtual leg illusion questionnaire. *Ownership*: The ratings of the experienced illusory ownership were higher when the participants were seeing the virtual legs (*Body similarity*: $p = 0.001$), when the dummy legs or objects were seen from the first-person viewpoint (*Visuo-spatial viewpoint*: $p = 0.008$) and when the visuo-tactile stimulation was synchronous (*Synchrony*: $p = 0.024$). *Illusory touch*: The strength of the experienced illusory touch was stronger in the conditions where participants saw the virtual legs (*Body similarity*: $p = 0.047$), when the legs or objects were presented in the first-person viewpoint (*Visuo-spatial viewpoint*: $p = 0.044$), and when the visuo-tactile stimulation was synchronous (*Synchrony*: $p < 0.001$). *Illusion of motor agency*: The sense of motor agency was the strongest during the condition where the virtual legs were seen in the first-person viewpoint and stimulated in synchrony with participants' real legs (three-way interaction: $p = 0.027$). *Illusion of proprioceptive rotation*: The illusory sense that legs have changed position was rated the strongest in the conditions where the visuo-tactile stimulation of virtual legs or objects was synchronous and they were presented in the third-person viewpoint (*Visuo-spatial viewpoint* × *Synchrony*: $p = 0.001$). The error bars depict the standard error of the mean. Sync, Synchronous; Async, Asynchronous; 1 POV, First-person viewpoint; 3 POV, Third-person viewpoint; LEGS, Dummy legs; OBJECT, Wooden objects. $^{**}p < 0.01$.

distractors were mapped were not aligned with the somatotopic coordinates of the vibro-tactile stimuli). Similar findings have been reported for hands, where the tactile stimuli were remapped to the location of visual distractors superimposed over rubber hands, but only when they were spatially aligned with the subject's real hands, and not when rotated by 90°, even if this posture is physically possible for the hands but not for the legs (Pavani et al., 2000). Comparable effect of the viewpoint on the RT CCE was also shown for the whole body (Maselli and Slater, 2014). Altogether, our CCE results suggest that the multisensory representation of the lower limbs is susceptible to changes of the visual reference frame, as shown for hands and trunk

(Tsakiris and Haggard, 2005; Costantini and Haggard, 2007; Heed and Röder, 2012). The first-person visuo-spatial viewpoint thus contributes to successful integration of leg-related visuo-tactile stimuli.

Contrary to our predictions, the synchrony of visuo-tactile leg stimulation prior to the CCE task did not significantly modulate the CCE score, while it instead increased the subjective sense of body ownership as assessed by the questionnaire (see below). The lack of a synchrony effect shows that the congruent visual and proprioceptive information about appearance and position of the legs alone was sufficient to induce the observed changes in the CCE performance, without requiring additional visuo-tactile synchronous tapping (Pavani et al., 2000; Slater et al., 2010; Maselli and Slater, 2013, 2014; van Elk et al., 2013). Alternatively, as the delivered visual and vibrotactile stimuli in the crossmodal congruency task are temporally synchronized, the task itself might have generated some effects, resembling those of the illusion *per se* and canceling out any condition difference due to prior visuo-tactile tapping. Similar findings on the lack of the visuo-tactile tapping synchrony effect on the CCE have been reported for the rubber hand, where the vibro-tactile and visual stimuli were presented simultaneously (Zopf et al., 2010) and for the full-body illusion, when a temporal delay of 33 ms was used (Aspell et al., 2009). However, when a larger delay of 150 ms (Zopf et al., 2010) or 233 ms (Aspell et al., 2009) was introduced between the visual and vibro-tactile stimuli, the CCE was significantly modulated, also by the synchrony of prior stroking. Thus, simultaneous presentation of visual and vibro-tactile stimuli during the present CCE measurements might have reset any synchrony-specific effect due to previous stimulation (Zopf et al., 2010).

Multisensory Representation of Upper and Lower Body Parts

The present study can also offer an insight into potential differences between upper and lower extremities in terms of their multisensory representation. Although our results cannot be directly compared to the existing studies due to different methodologies, experimental designs, and because we did not measure hand responses in the present study, some considerations are merited. Thus, our CCE results closely relate to the study of Pavani et al. (2000), which showed that anatomically incongruent posture of the rubber hand (rotated by 90°) reduces the CCE, which was comparable to the level where no rubber hand was presented in that study. However, a series of studies demonstrated that showing a photograph or a contour drawing of a hand during a CCE task resulted in relatively high CCE amplitude even if the presented hand image was rotated by 45 or 180°, or shown orthogonally to the participant's real hand (Igarashi et al., 2004, 2007). Compared to the results of the present study, where the presentation of lower limbs in a tilted orientation significantly decreased CCE magnitude (but not completely abolished it), these previous findings indicated that the hands' multisensory representation and its surrounding space might be more plastic than those of the lower extremities. Only few studies directly compared the multisensory representation of feet and hands and showed that the feet representation does not differ from that of the hands as inferred from the temporal order judgment tasks and CCE (Schicke and Röder, 2006; Schicke et al., 2009; van Elk et al., 2013). However, it was shown that anatomical incongruence and crossed posture modulated the CCE for the hands but not for the feet, indicating that visual information might be more strongly integrated with tactile and proprioceptive signals for the hands as compared to the feet (van Elk et al., 2013).

Although differences in the multisensory representation between upper and lower extremities might be assumed due to the fact that normally, hands can be positioned in different orientations and are used for frequent manual actions (providing greater variability of visual and proprioceptive information regarding their location than legs), we cannot conclude based on our leg data whether these differences exist, requiring direct comparisons between upper and lower limbs in sensitivity (or robustness) to various deviations from the habitual first person viewpoint.

Subjective Experience of Embodiment

At the phenomenological level, all three experimental factors—corporeal similarity, first-person visuo-spatial viewpoint and synchrony of stroking contributed to the illusory sense of ownership over virtual legs and illusory touch.

The present study confirms a large body of data showing that bottom-up as well as top-down signals contribute to the sense of hand and full-body ownership, and is thus in accordance with previous studies using the RHI paradigm, which demonstrated that sense of ownership for a hand emerges from spatiotemporal congruence of visual, tactile and proprioceptive cues as well as pre-existent body representations, including the anatomical resemblance (Tsakiris and Haggard, 2005), rules of general body configuration (Farne et al., 2000; Pavani et al., 2000; Austen et al., 2004; Ehrsson et al., 2004; Tsakiris and Haggard, 2005) and laterality (Tsakiris and Haggard, 2005; Tsakiris, 2010; Tsakiris et al., 2010). The present data conforms to a neurocognitive model of body-ownership based on the rubber hand illusion (Tsakiris, 2010) and extends its validity to the lower extremities. According to that proposal, the experience of illusory ownership is established by first comparing the visual, anatomical and structural characteristics of the viewed object with a pre-existing body model, and secondly, the current postural and anatomical features of own body with those of the viewed object. Then the system compares the reference frames of current synchronous visual and tactile input, and resolves the multisensory conflict by recalibrating the visuo-tactile coordinates into a unique body-centered reference frame, leading to the touch referral and induction of body ownership. As predicted by the model and observed in our data, incongruences in anatomical shape characteristics between own physical legs and what was visually presented (such as wooden blocks), between postural features (such as discrepancy between actual and observed leg posture in the third-person viewpoint) and asynchronous visuo-tactile stimulation reduce the sense of ownership for the virtual legs. Our data, however, cannot inform whether the order of critical comparisons as suggested by the model is correct.

Important for understanding the different components of the sense of body ownership (Longo et al., 2008), the subjective reports in our study show discrepancy between experienced body ownership and illusory touch. Although illusory leg ownership was significantly modulated by the visuo-spatial viewpoint and corporeal similarity, illusory touch (i.e., perceiving the touch on the virtual leg or wooden object) was experienced also when the synchronous visuo-tactile tapping was applied to the wooden blocks, or when it was applied in the non-habitual visuo-spatial viewpoint. Similar findings were also reported before (for example: Lenggenhager et al., 2007; Hohwy and Paton, 2010, study 2). The fact that we observed a modulation of illusory touch without illusory leg ownership (in case of wooden objects or third-person viewpoint) indicates a dissociation of the two phenomena, contradicting arguments that illusory touch (or referral of touch) is a sufficient marker of body ownership (Makin et al., 2008). The dissociation between illusory touch and ownership was also found by a comprehensive principal component analysis of subjective reports on the RHI (Longo et al., 2008) and described in neurological patients with somatoparaphrenia, who deny ownership for their left hand, but nevertheless can feel being touched on the very hand (Aglioti et al., 1996; Bottini et al., 2002). Additional evidence for the dissociation between illusory touch and ownership stems from an ERP study on the RHI (Press et al., 2007), showing that synchronous visual and tactile stimuli enhance early somatosensory SEP components regardless whether the visual stimulus is applied to a life-like virtual hand or non-bodily object, whereas later negative SEP components were reported to increase only with respect to the anatomical resemblance of the viewed object, suggesting temporally distinct contributions of the bottom-up and top-down mechanisms to the RHI. Based on the present findings, the experience of illusory touch mainly depends on the temporal correlation of visuo-tactile stimuli and it is less affected by violations of anatomical and postural congruency, whereas in addition to the visuo-tactile spatiotemporal correlation, top-down effects such as first-person visuo-spatial viewpoint and anatomical resemblance determine the experience of illusory body ownership.

Comparing CCE Task and Subjective Experience of Ownership

A comparison between the present CCE task results and subjective ratings reveals several differences. First, the synchrony of visuo-tactile stimulation significantly increased the experience of illusory leg ownership in comparison to asynchronous stimulation as assessed by the questionnaire, whereas this difference was absent in the CCE results. As already mentioned earlier in the discussion, the discrepancy might stem from the simultaneous onset of vibro-tactile and visual cues in the CCE task, which might have been a form of synchronous multisensory stimulation directly modulating the leg ownership illusion potentially dominating the effects of prior stroking on the CCE results. Second, we have also observed differential contributions of the two experimental factors (visuo-spatial viewpoint and corporeal similarity) to the multisensory effects CCE and the explicit feelings (questionnaire) related to leg ownership. The magnitude of the CCE was modulated by the interaction between the two factors, i.e., the strongest effect was observed when the legs, and not the objects, were presented in the first person visuo-spatial viewpoint, whereas according to the item ratings, both experimental manipulations, independently of each other, affected the subjective experience of leg ownership.

These discrepancies suggest that both measures capture two related, but not fully overlapping processes. The CCE reflects the processing and integration of multisensory stimuli in peripersonal space. The change in the CCE induced by our experimental manipulation, therefore, at most reflects a modulation in the representation of the space surrounding the body part, which in turn may depend on the way that body part is represented and perceived. Questionnaire data, instead, tap on the subjective feeling related to body experience. Thus the strength of visuo-tactile interactions, as measured by the CCE, cannot be directly equated with the subjective sense of ownership, although changes in the CCE may reflect concurrent changes in body experience (Maravita et al., 2002a,b; Pavani and Castiello, 2004; Aspell et al., 2009; Zopf et al., 2010; Sengul et al., 2012; Maselli and Slater, 2014). Also, the brain activity associated with the integration of visual, tactile and proprioceptive information in the rubber hand illusion has been found in several brain regions, including ventral intraparietal sulcus, premotor cortex, lateral occipital complex, operculum and cerebellum (Ehrsson et al., 2004, 2005; Makin et al., 2007), whereas an increased brain activity associated with the conscious experience of ownership for a rubber hand has been observed only in the ventral premotor area (Ehrsson et al., 2004, 2005) and in the posterior insula (Tsakiris et al., 2007), again compatible with the presence of shared and distinct mechanisms.

Future research may address the open issues and limitations of the current study, and in particular investigate the relationship between multisensory integration and subjective sense of ownership. This could, amongst others, include probing the effects of different temporal delays between distractors and target stimuli on CCE and questionnaire measures. This could also be tested in the presence or absence of prior induction of illusion with visuo-tactile tapping.

CONCLUSION

In sum, the present study shows that decreased corporeal similarity and larger divergence from the habitual first-person viewpoint reduce the sense of ownership for lower extremities and lessen the integration of visuo-tactile stimuli. By using the virtual leg illusion the study contributes to the understanding of how the multisensory lower extremities are represented in the brain. Understanding the neural mechanisms and the determinants of conscious experience for hands and legs might have important translational application in patients with the central and peripheral neural damage affecting the functionality and the perception of one's own body (Ehrsson et al., 2008; Marasco et al., 2011; Lenggenhager et al., 2015). While many data are already available in the case of upper limb representation, knowledge concerning the lower limb is much poorer. Considering the large number of patients with disabilities affecting the lower-limbs, due to spinal cord injury or lower limb amputation, these available hand data on multisensory mechanisms and bodily experience may not be sufficient and need to be extended by leg data. Research on multisensory stimulation paradigms and bodily illusions modulating lower limb ownership might be particular relevant especially for technological devices and new rehabilitation protocols aimed at restoring lower limb functions. Our study on the one hand confirms the importance of top-down signals for leg representations and, on the other hand, proposes a sensitive and easy-to-apply paradigm to measure the extent of body ownership and embodiment specifically for the lower limb.

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3.2 BODY OWNERSHIP IN PARAPLEGIA: IMPLICATIONS FOR PAIN MANAGEMENT AND NEUROREHABILITATION

BODY OWNERSHIP IN PARAPLEGIA: IMPLICATIONS FOR PAIN MANAGEMENT AND NEUROREHABILITATION

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ABSTRACT

Objectives: To investigate leg ownership and its effect on neuropathic pain in patients with spinal cord injury (SCI) using multisensory own body illusions.

Methods: 20 SCI patients with paraplegia and 20 healthy control subjects (HC) participated in two factorial, randomized, repeated-measures design studies. In the Virtual Leg Illusion (VLI)[1] we applied a/synchronous visuo-tactile stimulation to the participant's back (either immediately above the level of the spinal cord injury or at the shoulder) and virtual legs as seen on a head-mounted display and tested the effect of the VLI on the sense of leg ownership (questionnaires) and on perceived neuropathic pain (visual analogue scale pain ratings). Illusory leg ownership was compared with illusory body ownership (induced in the Full Body Illusion; FBI)[2], by applying a/synchronous visuo-tactile stimulation to the participant's back and the back of a virtual body as seen on a head-mounted display.

Results: Our data show that SCI patients less readily integrate conflicting multisensory information to construct an illusory sense of leg ownership (as compared to HC), and that leg ownership decreased with longer time since SCI. No differences between both groups were found (in strength and selectivity) for body ownership as tested in the FBI. We report mild analgesia specific for synchronous visuo-tactile stimulation at the lower back position. Mild pain reduction was also present during the FBI, but was found in both experimental conditions.

Conclusions: Current findings show that the sense of leg ownership is altered in paraplegia and have important implications for SCI neurorehabilitation protocols.

INTRODUCTION

Spinal cord damage can cause permanent loss of sensory and motor functions as well as persistent neuropathic pain affecting the body below the level of the injury[3–5]. Sensorimotor deprivation in SCI leads to structural and functional changes in brain and spinal cord, following a somatotopic organization[3,6]. Recently, several studies showed that multisensory processing and the related sense of body ownership[7–9] is impaired in patients with SCI [10–12], suggesting that sensory impairments in SCI extend beyond unimodal deficits in the somatosensory or motor system. Body ownership and pain perception can be experimentally manipulated through body ownership illusions using multisensory stimulation[2,13–20]. However, previous studies in SCI patients only investigated ownership for the upper extremity[10,12,21]. Here, we investigated leg and whole body ownership in SCI patients, using adapted VLI[1] and FBI[2],respectively, and tested their potential analgesic effects. In the VLI, we simultaneously stroke virtual legs and the patient's nearest body site with preserved tactile perception, i.e. lower back to induce leg ownership and illusory tactile percepts on the legs. Based on the findings regarding cortical somatotopical reorganization after deinnervation of a body part[17], we predicted that synchronous stimulation of the lower back would result in stronger illusion and analgesia than stimulation of a more distant site, i.e. upper back. We further predicted that differences between SCI and controls would be found for the leg ownership (VLI), but not for the global sense of body ownership (FBI).

METHODS

Participants. 20 patients (2 females; 23 - 71 years, M = 47.3 ± 12.0 years) with SCI participated in the study. SCI was traumatic in 18, and non-traumatic in 2 cases. The time since injury varied between 3.5 months to 71 years (17.1 ± 18.1 years). According to the American Spinal Cord Injury Assessment[22] (ASIA) standards their lesions ranged from (T2) to lumbar (L2); 15 subjects had complete lesions (ASIA A), three sensory incomplete (ASIA B) and two sensory and motor incomplete (ASIA C) lesions. None of the SCI patients had a history of other neurological or psychiatric disease. 11 SCI subjects (SCI-pain) suffered from chronic neuropathic pain at and/or below the SCI level. Demographic and clinical data of the SCI group are summarized in Table 1. 20 healthy age-matched participants (2 females; 23 – 70 years, M = 43.0 ± 11.8 years; independent-samples two-tailed t-test: t(38) = 1.13, p = .975) were recruited as a control (HC) sample.

Protocol approvals, Registrations, and Patient Consents. The study protocol was approved by the local ethics committees and was conducted in accordance with the ethical standards of the Declaration of Helsinki. All participants were informed about the experimental procedure and gave their written informed consent prior to their participation in the studies.

Experimental paradigms and design.

VLI. We adapted the VLI protocol[1] to the present investigation of SCI patients. Due to the impairment of tactile perception in legs of the SCI patients, the visuo-tactile conflict was applied between the seen virtual legs and the back of a participant (tactile stimulation). The participants sat in a wheelchair and wore a head-mounted display (HMD; Fig.1A). Fake legs were placed on another chair, mimicking the usual sitting posture. A camera was located above them at the height and angle corresponding to the participant's first-person viewpoint. The real-time video recording was fed to the HMD to present to participants virtual legs, superimposed over their physical legs while the experimenter simultaneously stroked the participant's back and the corresponding upper dorsal part of the ipsilateral virtual leg. Tactile stimulation was applied on the lower lateral back (immediately above SCI level) or on the upper lateral back (distant, control site). Thus, the participants observed the virtual legs being touched simultaneously as they received touches on their physical back (Fig.1A). In a 2x2 repeated measures design we manipulated the *synchrony* between the stroking of the virtual legs (synchronous, asynchronous) and the participant's *back location* (lower or upper back). In the synchronous condition the stroking of the virtual legs was synchronized either with the stroking of the lower or the upper ipsilateral back. In the asynchronous conditions the experimenter applied temporally incongruent visuo-tactile stimulation (approximately 1 sec of delay) between virtual legs and the participant's back. Each condition lasted for 60 s.

FBI. Body ownership was manipulated through an adapted FBI protocol[2]. The participants sat in a wheelchair and wore an HMD. A camera was positioned 2 meters behind them and filmed participants' back that the experimenter stroked. The real time video of the stroking was projected onto the HMD. The participants thus viewed their own body projected in front of them (virtual body) being touched while at the same time receiving touches on their back (Figure1). This visuo-tactile stimulation was synchronous or asynchronous (800 ms of the video delay) and lasted for 60 seconds.

Assessments. The VLI was assessed with a 9-item questionnaire, adapted from body illusions studies[2,13,14], with items referring to the experienced ownership for the virtual legs, illusory touch, and referred touch. The FBI was assessed with a 7-item questionnaire, referring to the experienced ownership for the virtual body and illusory touch on the virtual body as reported previously[2]. Both questionnaires contained control items. All items shown in Table 2. The items were rated on a 7-point Likert scale, ranging from -3 (“not at all”) to +3 (“completely agree”). The intensity of actual neuropathic pain was assessed with a visual analogue scale (VAS), ranging from 0 (no pain) to 100 (worst pain imagined)[23]. The Cambridge depersonalization scale (CDS)[24] was used to assess the presence of unusual experiences (altered self-experiences and anomalous bodily experiences).

Procedure. A short semi-structured interview was first conducted with the SCI participants about their SCI, related pain, and bodily sensations; they were also asked to fill out the CDS. Before the experiment started, the experimenter carefully defined the level above which each patient had intact tactile perception on the back to ascertain that they easily detected tactile stimulations. All SCI-patients with neuropathic pain were asked to rate the intensity of currently perceived pain on the VAS (baseline). The VLI and FBI protocol were then carried out in a counter-balanced order across participants. After each experimental condition, the participants rated the current neuropathic pain intensity (only SCI-pain) on pain VAS, and answer the VLI or FBI questionnaire (all participants). The order of the VLI conditions was randomized across patients, and the order of the FBI conditions counter-balanced.

Statistical analyses. The FBI and VLI illusion questionnaire ratings were first ipsatized using individual mean rating[25] and then averaged based on the measured component (see Table 2). The scores of the VLI questionnaire were analyzed with a mixed ANOVA, where the factors *synchrony* (synchronous, asynchronous) and *back location* (lower back, upper back) were used as within-subjects factors and *group* (SCI, HC) as a between-subjects factor. The FBI questionnaire scores were analyzed with a mixed design ANOVA, using *synchrony* (synchronous, asynchronous) as a within-subjects and *group* (SCI, HC*)* as a between-subjects factor. For the subgroup of SCI-patients with neuropathic pain (n=11), the baseline pain rating was first subtracted from the post-condition pain ratings to obtain measures of pain modulation (pain change), which were then analyzed with repeated measures ANOVA (VLI) and paired sample t-test (FBI). The significance (alpha) level used was 0.05. One-tailed one-sample t-tests were used to infer whether the pain change is significantly lower than zero. The significance levels of these comparisons were adjusted with the Bonferroni method (FBI: $\alpha_{corr} = \alpha/2 = 0.025$; VLI: $\alpha_{corr} = \alpha/4 = 0.0125$). A detailed description of the statistical analyses is given in the Supplemental material. The CDS ratings were scored accordingly to [24]. Based on a previous study showing increased occurrence of altered body perception in SCI[10], we focused the analyses on the items in the Anomalous Body Experience (ABE) subscale[26], using non-parametric Mann-Whitney U test for between-groups comparison.

RESULTS

VLI. We found significant main effects of *synchrony,* where synchronous visuo-tactile stimulation induced stronger experience of illusory ownership for the virtual legs (F(1,36) = 4.69, p = .037, $\eta_p^2 = .115$), stronger sensations of illusory touch F(1,36) = 8.01, p = .008, $\eta_p^2 = .182$) and stronger referred touch F(1,36) = 16.05, $p < .001$, $\eta_p^2 = .308$), without affecting the ratings of the control items (p = .112)

We found a significant main effect of *group* on the ratings of illusory ownership (F(1,36) = 5.26, p = .028, $\eta_p^2 = .128$), showing that SCI patients experienced weaker illusory leg ownership than the HC group independently of the *synchrony* of stroking (interaction: p = .263), whereas no such group differences were found in the ratings of illusory touch, referred touch or control items (all $p \geq .153$). These findings suggest that SCI experienced weaker leg ownership, but equally strong illusory touch sensations. No significant main effect of *back location* and no significant interaction effects were found (all $p \geq .063$). No differences in the illusion or control ratings were found between the SCI patients with preserved tactile sensation in the legs and the SCI patients with complete tactile loss (all $p \geq .096$).

A significant exponentially decaying relationship was found between duration of SCI and the magnitude of illusory leg ownership ($R^2 = .284$, F(1,18) = 7.15, p = .016) and between duration of SCI and the magnitude of illusory referred touch ($R^2 = .223$, F(1,18) = 5.16, p = .036), importantly, both findings were only observed in the condition in which the lower back was stroked synchronously (other conditions: all $p \geq .081$). No significant correlations were found between the illusory ratings and the level of SCI (all $p \geq .125$).

Concerning pain ratings, no significant main effects of *synchrony*, *back location*, or interactions were found on the change in pain ratings between the post-illusion and the baseline rating (all $p \geq .147$). However, when comparing the change in pain against zero we found a significant pain reduction when the lower back was stimulated synchronously with the virtual legs (one-tailed t-test: t(10) = -1.95, p = .04), but not in any of the other conditions (all p ≥ .188). However, the comparison did not survive the correction for multiple comparisons (α_{corr} = .0125). Results are shown in Figure 2. Detailed statistical results are reported in Supplemental material.

FBI. We found significant main effects of *synchrony,* where synchronous visuo-tactile stimulation induced stronger illusory body ownership (F(1,38) = 21.67, p < .001) and stronger illusory touch (F(1,38) = 72.38, p < .001, η_p^2 = .656) than asynchronous stimulation, but it did not modulate the ratings of control items (p = .823) We did not find significant main effects of *group* on any of the FBI questionnaire items (all p ≥ .558). The interaction effects were also not significant (all p ≥ .146).

No significant correlations were found between ratings on body ownership and illusory touch with SCI duration or with SCI level (all p ≥ .052).

Concerning pain ratings, the synchrony of visuo-tactile stimulation did not modulate the neuropathic pain ratings (pain change, t(10) = 0.10, p = .920, d = 0.042). However, the pain was significantly reduced by the FBI compared to baseline measurements in both the synchronous (t(10) = -2.37, p = .020) and asynchronous (t(10) = - 2.37, p = .020) visuo-tactile stimulation conditions. Results are graphically shown in Figure 3 detailed analyses are given in Supplemental material.

CDS. No significant differences between the SCI and CTRL group were found for the total CDS or ABE subscale scores (all p ≥ .260). However, statistically significant higher ratings by the SCI were found for two individual items: "*Parts of my body feel is if they didn't* *belong to me*" (Z = -2.20, p = .028) and "*I have to touch myself to make sure that I have a body or a real existence*" (Z = -2.61, p = .009).

DISCUSSION

We investigated SCI-related alterations of bodily self-consciousness through multisensory body illusion paradigms. In particular, we tested how the sense of leg and whole body ownership are affected by SCI, and whether such multisensory stimulation has analgesic effects on the perception of neuropathic pain. We found differences between the SCI and HC group in the experience of illusory leg ownership, as tested with the VLI. Contrarily, we found that the global sense of body ownership, as inferred through the FBI, is not affected by the SCI. We also show that both paradigms have potential analgesic effects.

In the VLI paradigm participants received tactile stimulation on their back while viewing virtual legs being touched by the experimenter. This manipulation, when temporally synchronous, induced stronger integration (as compared to asynchronous) of visual and tactile information, resulting in the illusory sensation that touching the virtual legs is causing the touch on the back (referred touch) and to a lesser extent illusory touch (feeling touch on the legs) in both SCI and HC groups. Important for understanding the impact of the SCI on lower leg representation are the differences between the SCI and CTRL group in the experience of illusory leg ownership. The SCI group showed a general reduction across conditions in proneness to incorporate virtual legs as one's own. This indicates that individuals with paraplegia less readily integrate the available visual and tactile information to experience illusory leg ownership. Time since injury also negatively correlated with the strength of illusory leg ownership and referred touch. Thus, with longer sensorimotor deprivation, an individual with SCI will less likely use currently available multisensory information to incorporate virtual legs into his body representation and probably rely stronger on an existent off-line leg representation. Similar finding was previously reported for upper limb amputees and the strength of the rubber hand illusion[27].

We did not observe stronger indices of illusion when the back near the lesion site was stimulated as compared to more distant, upper back. This would indicate that SCI-induced cortical reorganization in the primary sensory cortex (S1) was involved in the altered bodily-self as shown for a hand-face remapping effect in patients with tetraplegia during the RHI[12]. Alternatively, the absence of the stimulation site effect could also be due to relatively large receptive fields of mechanoreceptors on the back and smaller proportion of the back surface representation in the neural somatotopical organization of the S1. Thus, our paradigm might not be sensitive enough to reflect small differentiation between the areas representing lower and upper back in the S1, when explicit and subjective measures are used. Nevertheless, a negative correlation between the time since injury and the ratings of the VLI might indicate that certain SCI-related plasticity beyond the S1 does occur. This possibly includes multimodal regions (and their connections) associated with the integration of body-related sensory signals and sense of body ownership, such as the ventral premotor cortex, posterior parietal cortex and insula[8].

Contrarily to the illusory experience of leg ownership, we have not found any differences between the SCI and HC subjects in their experience of the FBI that, in comparison to paradigms where the focus of the visuo-tactile stimulation is a body part (rubber hand illusion- RHI[14] or VLI[1]), enables experimental manipulation of global bodily-self consciousness, affecting the ownership for whole body and perceived self-location[2,28]. In the current study we extended existing findings[2,29], showing that synchronous (as compared to asynchronous) visuo-tactile stimulation induces stronger illusory ownership in HC as well as SCI subjects, suggesting that the chronic deinnervation of the lower trunk and legs in SCI does not alter the basic multisensory mechanisms necessary for generating a coherent sense of bodily self. Also, the visuo-tactile stimulation was applied to the body site with fully preserved sensory and motor functionality (upper trunk), which was previously shown to induce changes in global sense of body ownership[2,29,30]. In this regard our SCI sample did not differ from the control group, and this may account for the current findings.

We also investigated whether our experimental paradigms have an analgesic effect on the experienced neuropathic pain. We observed a specific trend in the VLI, where visuo-tactile stimulation of the back nearest to the lesion level in synchrony with the virtual legs resulted in near significant reduction of rated neuropathic pain. The somatotopy-related analgesia suggests that this particular experimental manipulation might activate otherwise silent cortical regions representing lower limbs. The stimulation has thus possibly transiently attenuated the mismatch between visual information and (absent) tactile and proprioceptive inputs, one of the neural mechanisms proposed to explain the origins of neuropathic pain[18,31]. In accordance with the explanation, reducing sensory mismatches through rubber hand illusion has been shown to alleviate neuropathic pain in upper limb amputees[18]. On contrary, we found a general analgesic effect of the FBI regardless of the condition. This effect is possibly driven by the visual feedback about own body as previous studies have indeed shown that seeing one's own body has an analgesic effect on the perception of inflicted pain intensity[16,32,33]. Such visual analgesia operates through a functional coupling between visual body and pain neural networks[34]. Alternatively, the observed analgesic effect of the FBI paradigm could also be explained by the distraction effect of immersion in the virtual reality[35].

Our results should be, however, interpreted with caution, as the SCI sample with neuropathic pain was small and heterogeneous in neurological level, lesion onset time and type of the lesion. Therefore the results need to be replicated in a larger cohort of SCI patients with chronic pain, preferably using prolonged and repeated stimulation, in order to draw firmer conclusion about the analgesic effects of the paradigm.

In conclusion, the current study elucidates how massive body deinnervation in SCI alters the bodily self, and how multisensory signals can be integrated to modify bodily perception and attenuate pain. We have shown that the sense of body ownership is compromised in individuals with SCI as tested through the body illusions and also assessed with CSD (for similar finding see also [10]). The current findings have important implications for the development and planning of neurorehabilitation and pain management protocols, which should be focused at early interventions to restore and strengthen the sense of own body in the SCI population.

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TABLES

Table 1. Demographic and clinical information of the SCI subjects

ID	AGE (years)	GENDER	SCI DURATION (years)	NLI	AIS	ETI	SPASMS	PAIN	PTS LEGS
1	30	M	0.8	L2	C	T	+	+	+
2	54	M	12	T8	A	Ch	+	+	+
3	42	F	3	T2	A	T	+	+	-
4	48	M	2.5	T7	A	T	+	+	-
5	34	M	0.3	T10	A	T	+	+	+
6	28	M	0.3	T10	A	T	-	+	+
7	47	M	8	T10	C	T	+	+	+
8	40	M	7	T5	A	T	-	+	-
9	61	M	27	T8	A	T	+	-	-
10	47	M	21	L1/L2	B	T	-	-	+
11	60	M	21	T6	A	T	+	-	-
12	23	M	4	T3	A	T	+	-	-
13	52	M	22	T6/T7	A	T	+	-	-
14	52	M	32	T3/T4	B	T	+	-	+
15	57	M	39	T12	B	T	-	-	+
16	49	M	25	L1	A	T	+	-	+
17	48	M	4	T4/T5	A	T	+	+	-
18	58	M	38	T8	A	T	+	+	+
19	71	F	71	T12	A	Co	-	+	+
20	44	M	4	T4	A	T	+	-	-

Demographic and clinical data of the subjects with SCI who participated in the study. SCI DURATION = time elapsed between the injury and the experimental session, NLI = Neurological Level of Injury, AIS = Asia Impairment Scale, ETI = etiology of the SCI: traumatic (T), chemically induced (Ch), congenital (Co), PAIN = neuropathic pain, + or – marks the presence or absence of spasms or neuropathic pain, PTS LEGS = any preserved tactile sensation in legs, L = left leg, R = right leg, B = bilateral, or absent (-).

Table 2. Questionnaire items used to assess the experience of the FBI and VLI.

	Questionnaire items in the FBI	
1	It seemed as if I was feeling the touch of the stick at the location where I saw the virtual body being touched.	Illusory touch
2	It seemed as though the touch I felt was caused by the stick touching the virtual body.	Illusory touch
3	I felt as if the virtual body was my body.	Ownership
4	I felt as if the virtual body was drifting towards my body.	Control
5	It seemed as if I might have more than one body.	Control
6	It seemed as if the touch I was feeling came from somewhere between my own body and the virtual body.	Control
7	It appeared (visually) as if the virtual body was drifting backwards (towards my body).	Control
Questionnaire items in the VLI		
1	I had the impression that the legs which I was looking at were my real legs.	Ownership
2	I had the impression as if the touch I saw was applied to my legs.	Illusory touch

3	I had the impression that the experimenter was touching my legs.	Illusory touch
4	I had the impression that the touch I felt (on the back) was caused by the stick touching the legs.	Referred touch
5	I had the impression that my legs were drifting towards my trunk.	Control
6	I had the impression that my legs were in the place of my trunk.	Control
7	I had the impression that my trunk was drifting towards my legs.	Control
8	I had the impression that the touch I felt came from somewhere between my legs and my back.	Control
9	I had the impression that my legs had changed position.	Control

FIGURES AND LEGENDS

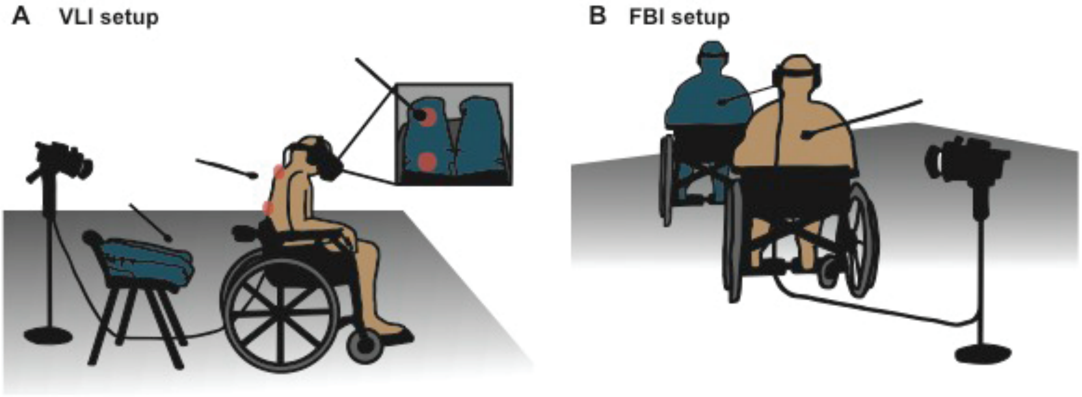

Figure 1. Experimental setups. (A) In the VLI paradigm, the participant sits in a wheelchair and wears an HMD and headphones. The experimenter simultaneously strokes the lower or upper part of participant's back and the corresponding part of the dummy leg. The camera films dummy legs from the distance and angle that corresponds to the participant's first-person viewpoint, and the real-time video recording is projected onto the HMD. Thus, the participant sees touch cues applied to the virtual legs while being touched on his back. (B) In the FBI paradigm, the participant sits in a wheelchair and wears headphones and an HMD. A video camera, standing 2 m behind, films participant's back, while the experimenter is applying tactile stimulation to the participant's back with a wooden stick. The real-time (delayed for 800 ms in asynchronous condition) video is projected onto the HMD. The participant thus sees his own virtual body projected in front and being touched with the stick, while in the same time feels being touched on the back.

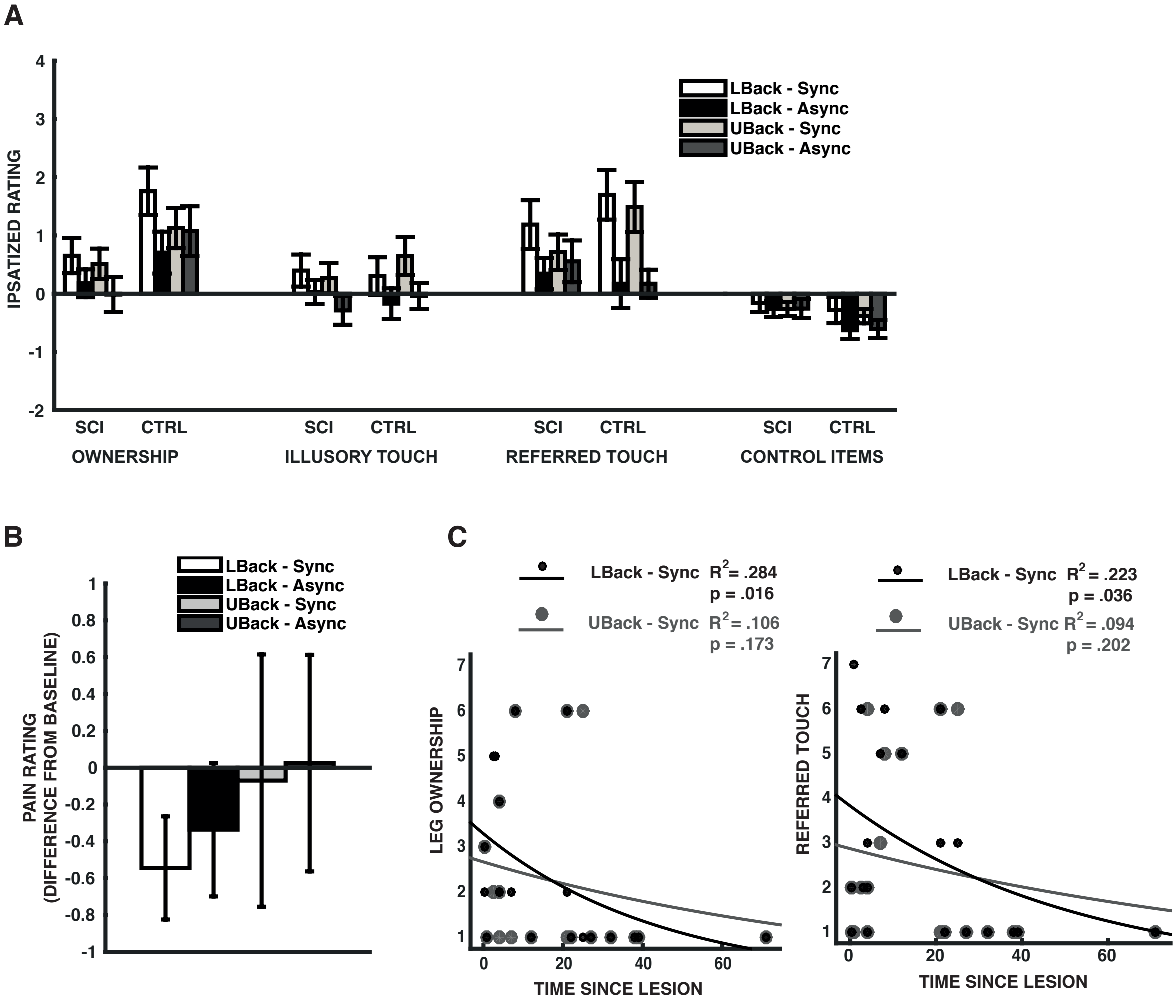

Figure 2. VLI results (A) Mean ipsatized ratings of the VLI questionnaire items: significant main effects of synchrony were found for the ratings of ownership, illusory touch and referred touch. Significant main effect of group was found for the ratings of ownership. (B) Mean differences in neuropathic pain between baseline and post-condition ratings in the VLI. (C) Exponential decaying relationship between the time since lesion and ratings of ownership (left) or referred touch (right) in the VLI: significant relationships between the illusion and time since lesion were found for synchronous stimulation of lower back, but not upper back. *SCI = spinal cord injury group, CTRL = control group, Sync = synchronous, Async = asynchronous, L Back = lower back, U Back = upper back.* Error bars show standard error of the mean.

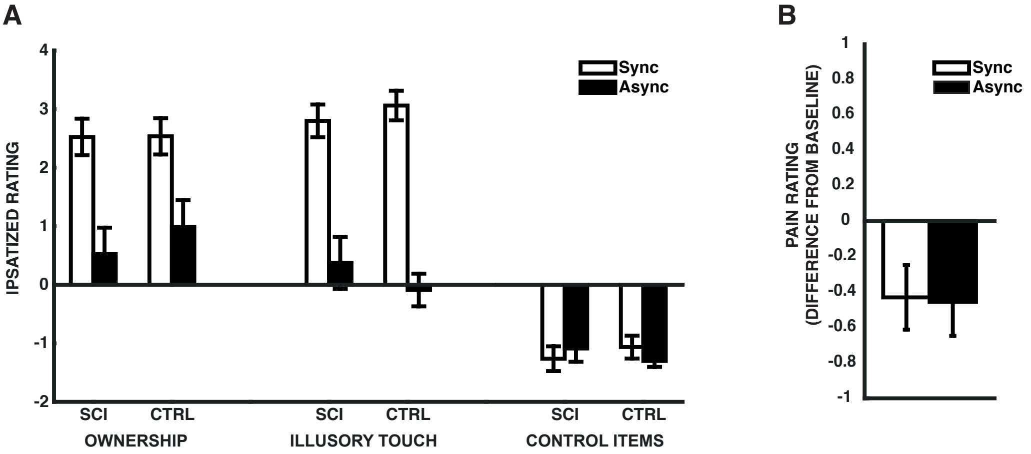

Figure 3. FBI results (A) Mean ipsatized ratings of the FBI questionnaire items: significant main effects of synchrony were found for the ratings of ownership and illusory touch, but not for control items. The differences between the groups were not significant. (B) Mean differences in neuropathic pain between baseline and post-condition ratings for synchronous and asynchronous condition in the FBI: significant main effect of synchrony was found for the ratings of ownership, illusory touch and referred touch. Significant main effect of group was found for the ownership ratings. *SCI = spinal cord injury group, CTRL = control group, Sync = synchronous, Async = asynchronous.* Error bars show standard error of the mean.

DATA SUPPLEMENT

APPENDIX

A METHODS

B RESULTS

A METHODS

1.1 Statistical analysis

Questionnaire ratings. Due to the ordinal type of the questionnaire data, the ratings of the VLI and FBI illusion were first ipsatized by subtracting the subject's average value of all his ratings on the questionnaire from individual rating value[30]. For the VLI questionnaire, two items referring to the illusory touch and 5 control items were first averaged and then entered into the analysis (for questionnaire items see Table2). Similarly, for the FBI questionnaire, the average of two item ratings referring to illusory touch, the rating of ownership and the average of four control items were entered into the analysis. The ipsatized scores of the VLI questionnaire were analyzed with a mixed ANOVA, where 2 factors: *synchrony* (synchronous, asynchronous) and *back location* (lower back, upper back) were used as within-subjects factors and *group* (SCI, CTRL) as a between-subjects factor. The FBI questionnaire scores were analyzed with a mixed design ANOVA, using *synchrony* (synchronous, asynchronous) as a within-subjects and *group* (SCI, CTRL*)* as a between-subjects factor. A baseline pain rating was first subtracted from the post-condition pain ratings, which were then analyzed with either 2-way repeated measures ANOVA (VLI) or 2-tailed paired sample t-test (FBI). The significance (alpha) level used was 0.05. We compared the SCI patients with preserved tactile sensitivity (PTS, N =11) in the L1, L2 or L3 dermatome and SCI patients without any PTS (N = 9) in L1, L2 or L3 to infer whether differences in the illusory experiences exist between them. A mixed ANOVA was performed on the illusory ratings, with two within-subjects factors: *synchrony* (synchronous, asynchronous) and *back location* (lower back, upper back), and *leg PTS* (PTS, no-PTS) as a between-subjects factor.

Due to a restricted and small area of tactile sensitivity on the back of one T2 SCI subject, applying separate tactile stimulation to lower and upper back was impossible. For this reason the tactile stimulation applied near the lesion level was considered as lower-back condition, and no stimulation was performed for upper-back conditions. The data of this subject and his/her age and gender-matched control were not included in the ANOVA of the VLI questionnaire and pain data.

Pain ratings. The baseline pain rating was first subtracted from each post-condition rating. The rating differences were then analyzed with either one-way repeated measures ANOVA (FBI), with *synchrony* as the within-subjects factor, or two-way repeated measures ANOVA (VLI) with *synchrony* and *back location* as two within-subjects factors. In order to infer the analgesic effect of each condition, one-tailed one-sample t-tests were used to test whether the pain ratings differences were significantly lower than zero. The Bonferroni method of correction for multiple comparisons was used to adjust the level of significance (FBI: $\alpha_{corr} = \alpha/2 = 0.025$; VLI: $\alpha_{corr} = \alpha/4 = 0.0125$).

CDS The CDS ratings were scored accordingly to[27]. Based on a previous study showing increased occurrence of altered body perception in SCI[7], we focused on the analyses of the items in the Anomalous Body Experience (ABE) subscale[29], using non-parametric Mann-Whitney U test.

Correlations. The questionnaire data was transformed to non-zero positive values by adding a constant of 4 to all ratings. Linear and exponential curve estimations were performed for the relationship between the time since lesion and questionnaire ratings in the synchronous condition in the FBI in the synchronous - lower back and synchronous – upper back conditions in the VLI. Similarly, the linear and exponential curve estimations were performed for the relationships between the questionnaire ratings and the SCI level. The SCI level was considered as an integer ascribed to the ASIA-defined lesion level, ranging from 1 (lesion at T2) to 13 (lesion at L2). For the patients were the lesion was defined between two neurological levels, the score was defined as the average of two integers (for example: a T6/T7 lesion was scored with 5.5). The level of significance used was 0.05.

B RESULTS

1 VLI

1.1 Questionnaire ratings

Ownership. Statistical analysis showed that participants experienced stronger illusory ownership over virtual legs when the visuo-tactile stimulation was synchronous (M = 0.93, SEM = 0.20) as compared to when it was asynchronous (M = 0.48, SEM = 0.21; F(1,36) = 4.69, p = .037, η_p^2 = .115). No significant effect with regard to body part being stimulated was found on the rated illusory ownership (lower back: M = 0.75, SEM = 0.20; upper back: M = 0.67, SEM = 0.21; F(1,36) = 0.19, p = .665, η_p^2 = .005). On average, the SCI participants rated experienced illusory ownership over virtual legs as less strong (M = 0.29, SEM = 0.26) than the control group (M = 0.67, SEM = 0.21; F(1,36) = 5.26, p = .028, η_p^2 = .128). Non-significant were also the two way interactions between synchrony and body site (F(1,36) = 1.29, p = .263, η_p^2 = .035), between synchrony and group (F(1,36) = 0.02, p = .899, η_p^2 < .001), and between body site and group (F(1,36) = 0.02, p = .885, η_p^2 = .001). Non-significant was also the three-way interaction between the synchrony, body site and group (F(1,36) = 3.59, p = .066, η_p^2 = .091). No differences in the ratings of illusory ownership were found between the SCI patients with preserved tactile sensation in legs and those without (all p ≥ .096).

Illusory touch. The strength of experienced illusory touch was significantly modulated by the synchrony of visuo-tactile stimulation (synchronous: M = 0.40, SEM = 0.16; asynchronous: M = -0.12, SEM = 0.14; F(1,36) = 8.01, p = .008, η_p^2 = .182), but not by the body part being stroked (lower back: M = 0.14, SEM = 0.16; upper back: M = 0.15, SEM = 0.15; F(1,36) < 0.01, p = .974, η_p^2 < .001). No significant differences between the SCI (M = 0.10, SEM = 0.17) and control group (M = 0.19, SEM = 0.17) were found in the ratings of illusory touch (F(1,36) = 0.13, p = 0.721, η_p^2 = .004). Non-significant were also the two way interactions between synchrony and body site (F(1,36) = 0.70, p = .407, η_p^2 = .019), between synchrony and group (F(1,36) = 0.10, p = .749, η_p^2 = .003), and between body site and group (F(1,36) = 1.35, p = .253, η_p^2 = .036). Non-significant was also the three-way interaction between the synchrony, body site and group (F(1,36) = 0.003, p = .956, η_p^2 < .001). No differences in the ratings of illusory touch were found between the SCI patients with preserved tactile sensation in legs and those without (all p ≥ .107).

Referred touch. The strength of experienced referred touch was stronger when the visuo-tactile stimulation was synchronous (M = 1.27, SEM = 0.24) as compared to when it was asynchronous (M = 0.31, SEM = 0.18; F(1,36) = 16.05, p < .001, η_p^2 = .308). The strength of referred touch was not modulated by the body part being touched (lower back: M = 0.85, SEM = 0.21, upper back: M = 0.73, SEM = 0.20; F(1,36) = 0.36, p = .552, η_p^2 = .010). No significant differences between the SCI and control participants were found in the strength of experienced referred touch (SCI: M = 0.70, SEM = 0.25, control: M = 0.88, SEM = 0.25; F(1,36) = 0.26, p = .612, η_p^2 = .007). Non-significant were also the two way interactions between synchrony and body site (F(1,36) = 1.22, p = .278, η_p^2 = .033), between synchrony and group (F(1,36) = 3.69, p = .063, η_p^2 = .093), and between body site and group (F(1,36) = 0.004, p = .947, η_p^2 < .001). Non-significant was also the three-way interaction between the synchrony, body site and group (F(1,36) = 0.34, p = .563, η_p^2 = .009). No differences in the ratings of referred touch were found between the SCI patients with preserved tactile sensation in legs and those without (all p ≥ .291).

Control items. The ratings of control items were not modulated by synchrony of visuo-tactile stimulation (synchronous: M = - 0.27, SEM = 0.10, asynchronous: M = - 0.44, SEM = 0.09; F(1,36) = 2.66, p = .112, η_p^2 = .069) nor by the stimulated body part (lower back: M = -0.33, SEM = 0.10, upper back: M = -0.38, SEM = 0.09; F(1,36) = 0.21, p = 0.647, η_p^2 =.006). The SCI and control participants did not significantly differ in their ratings of control items (SCI: M = -0.24, SEM = 0.12; control: M = -0.48, SEM = 0.12; F(1,36) = 2.13, p = .153, η_p^2 = .056). Non-significant were also the two way interactions between synchrony and body site (F(1,36) = 1.50, p = .229, η_p^2 = .040), between synchrony and group (F(1,36) = 1.36, p = .252, η_p^2 = .036), and between body site and group (F(1,36) = 0.001, p = .978, η_p^2 < .001). Non-significant was also the three-way interaction between the synchrony, body site and group (F(1,36) = 0.003, p = .958, η_p^2 < .001). No differences in the ratings of control items were found between the SCI patients with preserved tactile sensation in legs and those with complete tactile loss (all p ≥ .096).

1.2 Correlations between the ratings of the illusion, time since lesion and lesion level

A significant exponentially decaying relationship was found between the strength of experienced illusory ownership in the *lower back – synchronous* condition and the time since the SCI (R^2 = .284, F(1,18) = 7.15, p = .016). The participants' predicted rating of illusory ownership is equal to $2.68 * e^{\mathbf{-0.2*lesion\ time}}$. On the other hand, the relationship between illusory ownership and time since lesion in the *upper back – synchronous* condition were non-significant (linear: R^2 = 0.050, F(1,17) = 0.90, p = .357; exponential: R^2 = 0.106, F(1,17) = 2.02, p = .173)

A significant exponentially decaying relationship was also found between the strength of experienced referred touch in the *lower back – synchronous* condition and the time since the SCI (R^2 = .223, F(1,18) = 5.16, p = .036). The participants' predicted rating of illusory ownership is equal to $3.11 * e^{\mathbf{-0.2*lesion\ time}}$. Non-significant relationship was found between referred touch and time since lesion for the *upper back – synchronous* condition (linear: R^2 = .051, F(1,17) = 0.91, p = .355; exponential: R^2 = .094, F(1,17) = 1.77, p = .202).

Non-significant relationships were found between the rating of illusory touch and the time since lesion in *the lower back – synchronous* (linear: R^2 = .097, F(1,18) = 1.93, p = .181; exponential: R^2 = .160, F(1,18) = 3.43, p = .081) as well in the *upper back – synchronous* condition (linear: R^2 = .020, F(1,17) = 0.34, p = .565; exponential: R^2 = .045, F(1,18) = 0.80, p = .385).

No significant correlations were found between the illusory ratings and the SCI level (all p ≥ .065).

1.3 Pain ratings

Statistical analysis showed that the pain ratings (difference from baseline) were not modulated by the synchrony of visuo-tactile stimulation (synchronous: M = - 0.34, SEM = 0.47; asynchronous: M = -0.11, SEM = 0.46; F(1,9) = 2.52, p = .147, η_p^2 = .219) nor by the body part being stimulated (lower back: M = -0.42, SEM = 0.33; upper back: M = -0.23, SEM = 0.63; F(1,9) = 1.04, p = .335; η_p^2 = .103). Non-significant was also the interaction between synchrony of visuo-tactile stimulation and body part being touched (F(1,9) = 0.72, p = .420, η_p^2 = .074). Comparing the rated pain against zero showed a reduction when lower back was stimulated in synchrony with the virtual leg (t(10) = -1.95, p = .04), however**,** the comparison did not survive the correction for multiple comparisons (α_{corr} = .0125). The other three experimental conditions did not significantly differ from zero (upper back – synchronous: t(9) = -0.10, p = .461; lower back – asynchronous: t(10) = -0.97, p = .188; upper back – asynchronous: t(9) = 0.04, p = .484).

2 FBI

2.1 Questionnaire ratings

Ownership. The analysis of questionnaire ratings showed that the participants on average experienced stronger illusion of ownership for their virtual body during synchronous visuo-tactile stimulation (synchronous: M = 2.53, SEM = 0.22, asynchronous: M = 0.76, SD = 0.322; F(1,38) = 21.67, p < .001, η_p^2 = .363).

No significant differences in the experience of illusory ownership for a virtual body were found between the SCI and control group (SCI: M = 1.53, SEM = 0.28; control: M = 1.76, SEM = 0.28; F(1,38) = 0.35, p = .558, η_p^2 = .009). Not significant was also the interaction between synchrony and group (F(1,38) = 0.35, p = .559, η_p^2 = .009).

Illusory touch. Synchronous visuo-tactile stimulation also resulted in higher ratings of illusory touch (synchronous: M = 2.93, SEM = 0.19; asynchronous: M = 0.14, SEM = 0.26; F(1,38) = 72.38, $p < .001$, $\eta_p^2 = .656$). The experienced intensity of the illusory touch did not differ between the two groups (SCI: M = 1.59, SEM = 0.23; control: M = 1.49, SEM = 0.23; F(1,38) = 0.10, p = 0.752, $\eta_p^2 = .003$). The interaction between synchrony and group was also not significant (F(1,38) = 1.22, p = .276, $\eta_p^2 = .276$).

Control items. The synchrony of visuo-tactile stimulation did not modulate the ratings of control items (synchronous: M = -1.16, SEM = 0.14; asynchronous: M = -1.20, SEM = 0.12; F(1,38) = 0.05, p = .823, $\eta_p^2 = .001$), nor did the ratings of differ between the SCI and control group (SCI: M = -1.18, SEM = 0.16; control: M = -1.18, SEM = 0.16; F(1,38) < 0.00, p = .972, $\eta_p^2 < .001$). The interaction between the synchrony and group was also not significant (F(1,38) = 2.21, p = .146, $\eta_p^2 = .055$).

2.2 Correlations between the ratings of the illusion, time since lesion and lesion level

Neither linear ($R^2 = .01$, F(1,18) = 0.12, p = .733) nor exponential relationship $R^2 = .001$, F(1,18) = 0.27, p = .872) between the illusory ownership and time since lesion were found significant. Non-significant were also the linear ($R^2 = 0.001$, F(1,18) = 0.02, p = .883) and exponential ($R^2 < 0.001$, F(1,18) = 0.01, p = .941) relationship between the time since lesion and intensity of illusory touch. No significant correlations were found between the illusory ratings and the SCI level (all $p \geq .059$).

2.3 Pain ratings

Statistical analysis showed that the pain ratings (difference from baseline) were not modulated by the synchrony of stroking (synchronous: M = -0.43, SEM = 0.18;

asynchronous: M = -0.46, SEM = 0.19; t(10) = 0.10, p = .920, d = 0.042). However, the differences between baseline and post-condition pain ratings significantly differed from zero in both, synchronous (t(10) = -2.37, p = .020) and asynchronous (t(10) = - 2.37, p = .020) condition.

3 CDS

No significant differences between the SCI and CTRL groups were found in the total CDS score (SCI: M = 25.0, SEM = 5.44; CTRL: M = 17.2, SEM = 3.67; Z = -1.125, p = .260), or in the ABE subscale score (SCI: M = 6.65, SEM = 2.05; CTRL: M = 3.8, SEM = 0.97; Z = -0.873, p = .383). Maximum variance between groups was found for the question items: "*Parts of my body feel is if they didn't belong to me*" (SCI: 2.6, SEM = 0.78, CTRL: M = 0.55, SEM = 0.22; Z = -2.20, p = .028) and "*I have to touch myself to make sure that I have a body or a real existence*" (SCI: M = 1.10, SEM = 0.50, CTRL: M = 0.0, SEM = 0.0; Z = -2.61, p = .009). The ratings of the other questionnaire items in the ABE subscale did not differ between the two groups (all p ≥ .075).

Part 2

3.3 CROSSING THE HANDS INCREASES ILLUSORY SELF-TOUCH

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Crossing the Hands Increases Illusory Self-Touch

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Abstract

Manipulation of hand posture, such as crossing the hands, has been frequently used to study how the body and its immediately surrounding space are represented in the brain. Abundant data show that crossed arms posture impairs remapping of tactile stimuli from somatotopic to external space reference frame and deteriorates performance on several tactile processing tasks. Here we investigated how impaired tactile remapping affects the illusory self-touch, induced by the non-visual variant of the rubber hand illusion (RHI) paradigm. In this paradigm blindfolded participants (Experiment 1) had their hands either uncrossed or crossed over the body midline. The strength of illusory self-touch was measured with questionnaire ratings and proprioceptive drift. Our results showed that, during synchronous tactile stimulation, the strength of illusory self-touch increased when hands were crossed compared to the uncrossed posture. Follow-up experiments showed that the increase in illusion strength was not related to unfamiliar hand position (Experiment 2) and that it was equally strengthened regardless of where in the peripersonal space the hands were crossed (Experiment 3). However, while the boosting effect of crossing the hands was evident from subjective ratings, the proprioceptive drift was not modulated by crossed posture. Finally, in contrast to the illusion increase in the non-visual RHI, the crossed hand postures did not alter illusory ownership or proprioceptive drift in the classical, visuo-tactile version of RHI (Experiment 4). We argue that the increase in illusory self-touch is related to misalignment of somatotopic and external reference frames and consequently inadequate tactile-proprioceptive integration, leading to re-weighting of the tactile and proprioceptive signals.The present study not only shows that illusory self-touch can be induced by crossing the hands, but importantly, that this posture is associated with a stronger illusion.

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Introduction

The skin defines the boundary of the organism and, as the largest human sensory organ, provides the most extensive interface with the environment through the tactile modality. Tactile information is also integrated with proprioceptive, visual, vestibular and auditory cues to construct multisensory representation of the body [1–4] and to generate the subjective experience of the body as one's own, i.e. body ownership [5–8]. Sense of body ownership also depends on the integration of motor signals [9–12], which by interaction with tactile perception, as in the case of self-touch, contributes to the self-awareness [13].

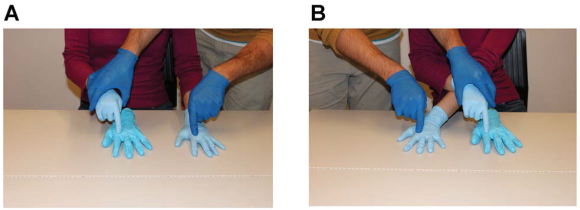
Localization of a tactile stimulus within external spatial coordinates comprises the location of the tactile cue on the body surface and its integration with proprioceptive signals [14]. These two processes are functionally and anatomically separated, relying on distinct neural mechanisms [15–18]. The tactile stimulus is first encoded with respect to a specific location on the skin (somatotopy) and processed by tactile neurons that have tactile receptive fields of varying size and location [19–22]. Then, in order to localize the touch in the external space, the tactile sensation is integrated with proprioceptive information about the current body position, as well as with the external signals from the visual and auditory system, and mapped into the common, external reference frame [14–16,23,24].

Several studies revealed that, when limbs are crossed, the integration of tactile with proprioceptive signals is hindered and localization of touch becomes less accurate [14,25]. For example, accuracy of temporal order judgments (TOJ; of two successive tactile stimuli applied to each hand) drastically decreases if arms are crossed (as compared to uncrossed arms posture) and may even lead to the inversion of temporal order judgments [15]. Related findings have been observed in a spatial stimulus-response compatibility task [26], covert attention tasks [27] and crossmodal congruency effect tasks [28,29].

However, little work has been done to study whether such "crossed hand effects" extend to the field of body ownership. An extensively used experimental protocol to manipulate hand ownership, generating the self-attribution of a fake hand via multisensory conflicts, is the rubber hand illusion (RHI) paradigm (the term *visual RHI* will be used further throughout the text). After observing a rubber hand that is placed next to and stroked in synchrony with one's own hand, hidden from view, participants report illusory self-attribution of the rubber hand. In this case, visual input dominates proprioceptive signals, inducing illusory sense of hand ownership for the fake hand [30–32]. The most common measures used to assess the illusion are questionnaire ratings and proprioceptive drift, i.e. shift of proprioceptively perceived location of one's own hand towards the rubber hand [30,31,33–36]. Importantly, illusory ownership decreases with larger visuo-proprioceptive spatial separations [32,37,38]. The illusion also decreases with lessened resemblance of the stroked object to a hand shape [36,39], and different handedness of the fake arm [35,36,38,40].

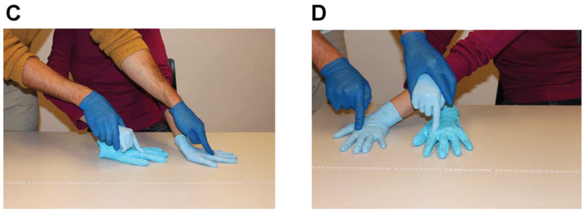
In the tactile, non-visual variant of RHI [41] (the term *tactile RHI* will be used further throughout the text), the RHI paradigm is modified, so that the experimenter moves the index finger of a blindfolded participant to stroke a rubber hand, while he strokes - at the same time - the corresponding part of the participant's other hand (see Figure 1). Synchronized stroking induces illusory self-touch, i.e. the illusion of touching one's own hand, while instead one is physically touching the fake hand [33,41–43].

We tested the tactile RHI paradigm in combination with a hand crossing manipulation in order to examine the effect of hand posture on the process of tactile-proprioceptive integration and induction of illusory self-touch (for a related example see [44]). We predicted that a "crossed hand effect" due to crossing of the hands during the tactile rubber hand illusion will modulate the strength of the tactile RHI. According to earlier observations [25,28,45] showing that crossing the hands impairs tactile-proprioceptive integration, such a posture manipulation may result in a decreased illusion. Alternatively, as impaired tactile-proprioceptive integration hinders the ability to localize tactile stimuli on one's own body, and therefore interferes with "standard" multisensory body representations, crossing the hands may lead to the increase of illusory self-touch. Such potential boosting of the illusion would be in itself novel finding because other postural manipulations have been shown so far to decrease the RHI effect.



Uncrossed posture

Crossed posture



Unfamiliar posture

Crossed in lateralized hemispace

Figure 1. Hand postures in the tactile RHI (Experiments 1–3). (A) *Uncrossed posture*: The rubber hand (middle finger) is aligned with the participant's body midline axis. The participant's left hand rests in the left hemispace, 20 cm away from the rubber hand (distance between both middle fingers). (B) *Crossed posture*: The rubber hand is aligned with the participant's body midline axis. The participant's left hand is crossed over the body midline and rests in the participant's right hemispace, 20 cm away from the rubber hand (distance between the middle fingers). (C) *Unfamiliar posture*: The rubber hand is rotated by 90 degrees to the participant's left; its MCP joint of the middle finger is aligned with the participant's body midline. The participant's left hand rests in his left hemispace and is turned in the same direction as the rubber hand. The distance between the MCP joint of the participant's left middle finger and the rubber hand's middle finger MCP is 20 cm. (D) *Crossed in lateralized hemispace*: The rubber hand is positioned in the participant's right hemispace, with the distance of 20 cm between the rubber hand middle finger and the participant's body midline. The participant's left hand is crossed under his right arm and rests in the right hemispace, 20 cm to the right of the rubber hand (distance between the middle fingers).
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We first report the results of three consecutive experiments in which we manipulated hand posture while inducing illusory self-touch in the tactile RHI. In Experiment 1 we explored the effect of crossing the hands on illusory self-touch and proprioceptive drift in the tactile RHI paradigm. The results confirmed the second hypothesis that crossing the hands across the body midline increased illusory self-touch as compared to uncrossed posture in the tactile RHI. However, crossing the hands did not modulate proprioceptive drift as compared to uncrossed hands posture. We next investigated whether the increase in the tactile RHI depends on the familiarity of the posture manipulation. Therefore we compared the strength of the illusory self-touch when participants had their hands in a standard uncrossed posture and when they were in an unfamiliar posture, i.e. with their left hand placed in the left hemispace and rotated by 90 degrees to the left (Experiment 2). Based on the evidence that hand position may not be only coded with respect to the body midline, but also in relation to the other hand [46–48], we further tested whether the increase in the tactile RHI is specific to crossing the body midline axis, or generalized to any crossing hands postures, independently from where they are placed in space (Experiment 3). Hence participants were presented with the tactile RHI paradigm while they kept their hands crossed across their midline or within their right hemispace. We found that the increase in the strength of the tactile RHI was not related to the unfamiliarity of the hand position (Experiment 2) and that the illusory self-touch was equally strengthened regardless of where in the peripersonal space the hands were crossed (Experiment 3). Finally, in Experiment 4, we explored whether the boosting effect of the crossed hand posture also applies to illusory hand ownership and proprioceptive drift in the visual RHI paradigm. Based on extensive evidence regarding the dominant role of vision over proprioception in estimating hand position and localizing tactile stimuli [49–52], we hypothesized that crossing the hands would not significantly affect the intensity of the illusory ownership in the visual RHI paradigm.

Materials and Methods

All participants were recruited by an advertisement on the EPFL campus (École Polytechnique Fédérale de Lausanne, Switzerland). They were fluent in English, right-handed and had normal touch perception as assessed by self-report. Each participant only took part in one experiment. All participants were naive to the purpose of the study and gave written informed consent to take part in the study. The study was approved by the local ethics committee (La Commission d'Ethique de la Recherche Clinique de la Faculté et de Medicine de l'Université de Lausanne) and was conducted according to the ethical standards laid down in the Declaration of Helsinki. Participants were reimbursed for their participation in the study with 10 CHF.

Experiment 1: Effect of crossing on illusory self-touch

Participants. 14 participants (1 female) participated in Experiment 1. Their age ranged from 22 to 35 years (M = 26.4 years, SD = 3.9 years).

Experimental design and procedure. We employed the tactile-proprioceptive paradigm from Ehrsson et al. [41] to induce illusory self-touch. The participant was seated behind a desk, wearing a blindfold to prevent any visual input and plastic gloves to match the tactile sensation of the rubber hand. The experimenter was stroking a gloved left rubber hand with the participant's right index finger while at the same time stroking the participant's left hand (Figure 1, part A). The left rubber hand was aligned with the participant's body midsagittal plane. The experimental design contained 2 within-subject factors: synchrony (asynchronous versus synchronous tactile stimulation) and hand posture (uncrossed versus crossed posture). The tactile stimulation of both hands, composed of alternating strokes and taps, was temporally and spatially matched in the synchronous conditions and unmatched in the asynchronous conditions. Note that in this tactile version of the rubber hand illusion there is a tactile-proprioceptive mismatch between the proprioceptive position of the passively stroking hand (touch cue at the stroked tip) and the proprioceptive position of the stroked hand (touch cue at the stroked hand; see Figure 1).

In the "uncrossed posture" condition, the participant's left hand rested in the participant's left hemispace, palm turned downwards with the middle finger being 20 cm from the body midline axis. A left dummy rubber hand was aligned with the body central sagittal plane. In the "crossed posture" condition, the participant's left hand crossed the body midline and rested in the right hemispace, again 20 cm from the body midline axis. The order of four conditions was randomized across participants. The tactile stimulation in each condition lasted for 60 seconds. Before and immediately after each condition the participant was asked to indicate the location of his left hand. For this we asked him to place his right middle finger above his left middle finger, without making any contact between them. The position of the right middle finger was recorded. The proprioceptive drift was defined as the difference between the pre- and post-stimulation measures. After each condition, the participant was also asked to answer the three-item questionnaire adapted from Ehrsson et al. [41]. The first item referred to illusory self-touch (*I felt like I was touching my hand*), while the other two served as control items for suggestibility (*I felt like I had another hand; I felt like my left hand was moving*). Here was asked to indicate on the 7-point Likert scale the intensity of subjective feeling described in each item (0 = not experienced at all, 6 = strongly experienced).

Experiment 2: Effect of unfamiliar posture on illusory self-touch

Participants. 14 (2 females) participants were involved in Experiment 2. Their age ranged between 24 and 29 years (M = 25.1 years, SD = 2.1 years).

Experimental design and procedure. In Experiment 2 we investigated whether the strength of illusory self-touch in the tactile rubber hand illusion was related to the unfamiliar posture of the hands in the crossed position. The same experimental design and procedure was used as in Experiment 1; however, instead of the crossed posture condition, we included an unfamiliar posture condition in the design and compared it with illusory self-touch in the uncrossed posture condition. In the "unfamiliar posture" conditions, the participant's left hand was placed on the table (in the left hemispace) and rotated by 90 degrees to the left. The rubber hand was turned in the same direction and rested on the midline axis, so the distance between the middle fingers' metacarpophalangeal (MCP) joints of the real and rubber hand was 20 cm (Figure 1, part B). Again, all tactile stimulations lasted for 60 seconds and the order of the four conditions was randomized across subjects. The subjective reports and the measure of proprioceptive drift were obtained in the same manner as in Experiment 1.

Experiment 3: Effect of crossing in lateralized hemispace on illusory self-touch

Participants. 15 participants (7 females) took part in Experiment 3. Their age ranged between 18 and 34 years (M = 24.2, SD = 4.1).

Experimental design and procedure. In Experiment 3 we investigated whether the increase in the illusory self-touch when hands were crossed was caused by crossing the body midline and thus positioning hands in the opposite hemispace or to crossing the hands per se (within the same hemispace for example). As in Experiment 1 two factors (synchrony and hand posture) were manipulated. The hand posture factor included "crossed posture" and "crossed in lateralized hemispace" conditions. The settings of the former are described in Experiment 1. In the "crossed in lateralized hemispace" condition, hands were crossed in the participant's right hemispace. The left hand was positioned 50 cm (the distance from the tip of the middle finger) from the body midline axis; while the rubber hand rested 30 cm away from the body midline axis in the same, right hemispace. The distance between the rubber and the stroked hand's middle finger was again 20 cm (Figure 1, part C). The experimental procedure and the outcome measures were the same as in Experiment 1.

Experiment 4: Effect of crossing in the visual RHI

In Experiment 4 we explored whether crossing the hands would affect illusory hand ownership and proprioceptive drift in the visual RHI paradigm [30].

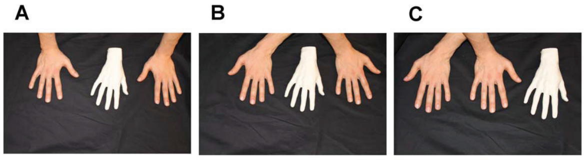
Participants. 14 participants (5 females) were participating in Experiment 4. Their age ranged between 21 and 29 years (M = 23.8, SD = 2.26).

Experimental design and procedure. A setup similar to the one described in Tsakiris & Haggard [36] was used and has been described previously to successfully induce the rubber hand illusion [53]. It consisted of a black wooden frame (100×50 cm), which was put on a desk in front of a participant and covered by a two-way mirror 23 cm above the desk. To occlude the sight of the participant's hands, a black paper was put under the mirror, leaving the middle third of the surface open to enable the view on the right rubber hand, which was placed in the centre of the wooden frame, aligned with the participant's body midline axis. A black fabric was installed inside the frame to occlude any side view of the participant's hands and forearms. Due to the two-way mirror the participant was able to see the rubber hand during tactile stimulation when the lights in the frame were turned on. During the proprioceptive judgment task, the rubber hand was hidden by putting the lights in the frame off, and a ruler on the top of the mirror was shown.

The experimenter placed the participant's hands inside the wooden frame. A right rubber hand was placed and aligned with the subject's midsagittal axis. The position of the hands was fixed depending on the experimental condition. In the "uncrossed posture" condition, the participant's hands were laid down in the anatomical position, with 40 cm of distance between both middle fingers. In the "crossed posture" the right hand was crossed over the left one, again, keeping 40 cm between both middle fingers. In the "crossed in lateralized hemispace" condition the participant's left hand was crossed under his right arm in his right hemispace. The same distance of 20 cm was kept between the rubber hand and the right hand middle fingers across all three conditions (Figure 2). In all conditions, the experimenter synchronously stroked and tapped the participant's right hand and the rubber hand. The latter was always in the same anatomical position as was the participant's stroked hand. However, depending on the condition it was not always positioned in the same hemispace. The order in which the three conditions were presented was randomized across participants. Before and after each condition, the participant was asked to make a proprioceptive judgment by verbally indicating on the ruler the perceived location of his right middle finger, while the hands were occluded from his vision. Rulers with a different onset were used for each proprioceptive judgment to prevent the participant from repeating the same value over the trials. After each condition, participants filled out the 9-item Visual Rubber Hand Illusion questionnaire, adapted from [30].

Data analysis

Questionnaire scores in Experiment 1, 2 and 3 significantly deviated from normal distribution (Shapiro-Wilk test of normality), therefore they were analysed with non-parametric statistical tests. First, the data sets were analysed with Friedman's ANOVA, and if significant, they were followed up with pair-wise comparisons, using the 2-tailed Wilcoxon's signed rank test. Three planned comparisons were made for each data set in the tactile RHI experiments, where the ratings of the two synchronous conditions were compared with their respective asynchronous pair, and those of the two synchronous, but different posture conditions, with each other. The p-values were corrected for multiple comparisons using the Bonferroni method, where $\alpha(\text{corrected}) = .05/3 = .0167$. The data acquired from the questionnaire ratings in Experiment 4 and proprioceptive drift measurements from all 4 experiments were analysed with repeated measures analysis of variance (ANOVA) and when required followed-up with two-tailed paired sample t-tests.



Uncrossed posture

Crossed posture

Crossed in lateralized hemispace

Figure 2. Hand postures in the visual RHI (Experiment 4). (A) *Uncrossed posture*: The rubber hand was positioned palm downwards and aligned (middle finger of the rubber hand) with the participant's body midline. The participant's hands were in their anatomical position each resting in its corresponding hemispace, 20 cm from the rubber hand (distance between the middle fingers). (B) *Crossed posture*: The rubber hand was aligned with the participant's body midline axis. The participant's right hand was crossed over the left one. Both hands rested on the desk, each with the distance of 20 cm to the rubber hand (distance between the middle fingers). (C) *Crossed in lateralized hemispace*: The rubber hand was again aligned with the participant's body midline axis. His left hand was crossed under his right arm in his right hemispace. The distance of 20 cm was kept between the rubber hand and the right hand middle fingers and 40 cm between the rubber hand and the left hand middle fingers.
doi:10.1371/journal.pone.0094008.g002

Results

Experiment 1: Effect of crossing on illusory self-touch

In Experiment 1 we explored how crossing the hands over the body midline affects illusory self-touch. Statistical analysis of the subjective ratings revealed that the reported strength of illusory self-touch (Item 1: *I felt like I was touching my hand*) significantly differed across the four conditions ($\chi^2(3) = 36.02$, $p < .001$). Using the adjusted α level of .0167 the follow-up Wilcoxon signed rank test revealed that participants rated the experience of self-touch stronger when the stroking was synchronous in uncrossed ($M = 3.36$, $SD = 1.60$; $Z = -3.071$, $p = .002$, $r = .580$) as well as in crossed hand postures ($M = 5.00$, $SD = 1.36$; $Z = -3.320$, $p = .001$, $r = .627$) as compared to asynchronous stroking (uncrossed: $M = 0.79$, $SD = 0.89$; crossed: $M = 1.43$, $SD = 1.34$). Importantly, having the hands crossed during synchronous tactile stimulation significantly increased the ratings of illusory self-touch as compared to the uncrossed posture condition ($Z = -2.700$, $p = .007$, $r = .510$). The observed increase in the illusion strength when hands were crossed was robust as 79% of participants rated the illusory self-touch at 4 or higher (compared to only 50% in uncrossed condition; χ^2 test: $p = .033$) (see Figure 3).

We further found that the mean of the illusory touch ratings after synchronous stimulation was significantly higher (adjusted α level = .0167) than the mean ratings on both control items in the crossed (Item1/Item2: $Z = -3.325$, $p = .001$, $r = .628$; Item1/Item3: $Z = = 3.204$, $p = .001$, $r = .606$) and uncrossed hand postures (Item1/Item2: $Z = -2.988$, $p = .003$, $r = .565$; Item1/Item3: $Z = -2.692$, $p = .007$, $r = .509$). The average ratings of the control Item 2 (*I felt like I had another hand*) did not significantly differ across the four conditions ($\chi^2(3) = 0.953$, $p = .813$). Significant differences in ratings were found for the control Item 3 (*I felt like my left hand is moving*) ($\chi^2(3) = 11.077$, $p = 0.011$). The planned post-hoc comparisons with the adjusted α level of .0167 revealed significantly higher ratings of the item in the uncrossed-synchronous conditions as compared to the uncrossed-asynchronous condition (Uncross Sync/Uncross Async: $Z = -2.536$, $p = .011$; Cross Sync/Cross Async: $Z = -1.361$, $p = .174$; Cross Sync/Uncross Sync: $Z = -.000$, $p = 1.000$). Taking into account the significant synchrony modulation of the Item 3 ratings, its use as a control item should be taken into consideration.

Drift analysis showed that the proprioceptive drift of the stimulated hand was greater in the synchronous versus asynchronous conditions ($F(1,13) = 10.365$, $p = .007$, $\eta_p^2 = 0.444$). No significant main effect of hand posture on the proprioceptive drift ($F(1,13) = 1.833$, $p = .199$, $\eta_p^2 = 0.124$) nor interaction between the synchrony of stroking and hand posture ($F(1,13) = .005$, $p = .945$, $\eta_p^2 = 0.000$) were observed.

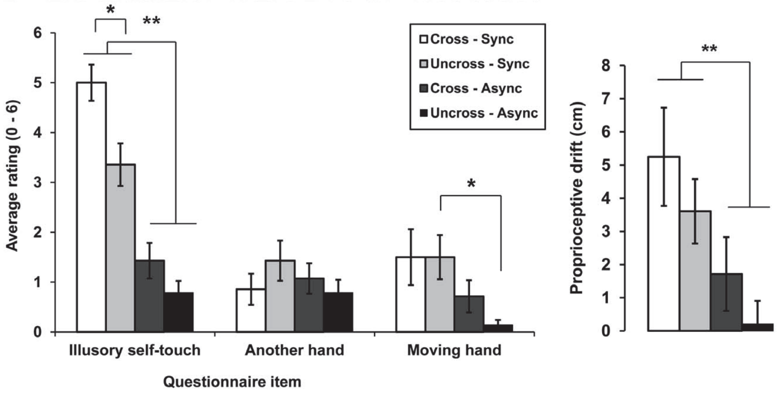
Experiment 2: Effect of unfamiliar posture on illusory self-touch

In Experiment 2 we tested whether the increase in illusory self-touch is due to the unfamiliar posture rather than to the crossing of the hands. Friedmann's ANOVA showed significant differences between the mean ratings of the four conditions ($\chi^2(3) = 30.487$, $p < .0001$). Post-hoc comparisons with adjusted α level of .0167 revealed that the participants rated illusory self-touch as more intense when the tactile stimulation was synchronous in familiar ($M = 3.93$, $SD = 1.69$) as well as in unfamiliar conditions ($M = 3.29$, $SD = 1.59$) as compared to asynchronous stroking (familiar: $M = 1.14$, $SD = 1.23$, $Z = -3.104$, $p = .002$, $r = .587$; unfamiliar: $M = 1.29$, $SD = 1.27$, $Z = -3.089$, $p = .002$, $r = .584$). Moreover, the illusion intensity in familiar and unfamiliar postures when the stroking was synchronized did not significantly differ

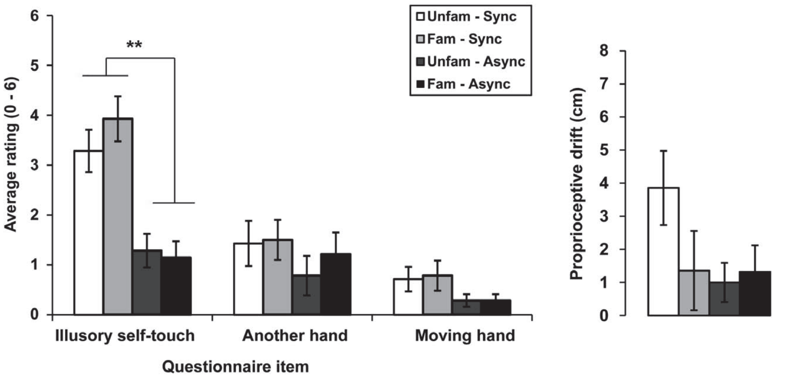
A TACTILE RHI QUESTIONNAIRE

Q1	**I felt like I was touching my hand.**	**"Illusory self-touch"**
Q2	I felt like I had another hand.	"Another hand"
Q3	I felt like my left hand was moving.	"Moving hand"

B EXPERIMENT 1: EFFECT OF CROSSING



C EXPERIMENT 2: EFFECT OF UNFAMILIAR HAND POSTURE



D EXPERIMENT 3: EFFECT OF CROSSING IN LATERALIZED HEMISPACE

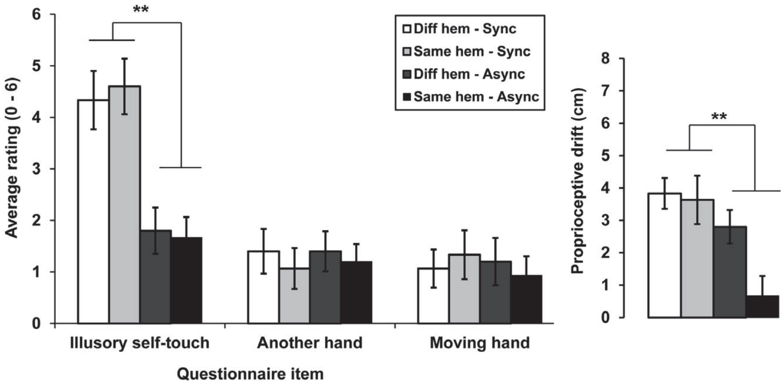


Figure 3. Questionnaire scores and proprioceptive drift results in the tactile RHI. (A) Questionnaire items adapted from [41] used in the Experiments 1 – 3. (B) Average questionnaire ratings and proprioceptive drift in Experiment 1. The participants reported stronger illusion in the synchronous as compared to asynchronous conditions. The illusion strength in the synchronous condition was enhanced when the hands were crossed as compared when uncrossed.Larger drift was observed in synchronous conditions.(C) Average questionnaire ratings and proprioceptive drift in Experiment 2. The participants reported stronger illusion in the synchronous conditions; however, no difference in the illusion strength was found between the familiar and unfamiliar hand posture. The proprioceptive drift did not significantly differ across the four conditions. (D) Average questionnaire ratings and proprioceptive drift in Experiment 3. The participants reported stronger illusion in the synchronous conditions; however, no difference in the illusion ratings were found between the synchronous conditions when hands were crossed over midline and when they were crossed in lateralized hemispace. The synchrony of stroking as well as crossing the hands over midline significantly increased the proprioceptive drift. The error bars depict the standard error of the mean. Sync = synchronous, Async = asynchronous, Cross = crossed, Uncross = uncrossed, Fam = familiar, Unfam = unfamiliar, Diff hem = crossed over midline, Same hem = crossed in lateralized hemispace.
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($Z = -1.809$, $p = .070$, $r = .342$), showing that the "crossed hands effect" on illusory self-touch does not depend on the familiarity of the posture. The between-subject comparison of the illusory self-touch ratings in the unfamiliar – synchronous condition with the ratings in the crossed – synchronous condition (Experiment 1) showed the latter to be significantly higher (Mann-Whitney U test: $Z = -2.743$, $p = .006$, $r = .518$). This comparison further indicated that the increase in the illusory self-touch was specific for crossed hand posture. The average ratings of the other two control items were low ($M \leq 1.5$, $SD < 1.70$). The statistical analysis showed that the ratings of Item 2 did not significantly differ across the four conditions ($\chi^2(3) = 6.000$, $p = .112$) whereas significant differences were found in the ratings for the Item 3 ($\chi^2(3) = 8.864$, $p = .031$); however, none of the planned comparisons using the adjusted α level of .0167 yielded significant differences (Familiar Sync/ Familiar Async: $Z = -2.121$, $p = .034$, $r = .401$; Unfamiliar Sync/ Unfamiliar Async: $Z = -1.656$, $p = .098$, $r = .313$; Unfamiliar Sync/Familiar Sync: $Z = -0.378$, $p = .705$, $r = .071$).

No significant main effect of synchrony ($F(1,13) = 1.72$, $p = .212$, $\eta_p^2 = 0.117$), hand posture ($F(1,13) = 2.30$, $p = .153$, $\eta_p^2 = 0.150$) nor interaction ($F(1,13) = 3.73$, $p = .076$, $\eta_p^2 = 0.223$) was found on the proprioceptive drift toward the rubber hand.

Experiment 3: Effect of crossing in lateralized hemispace on illusory self-touch

In Experiment 3 we explored whether the increase in illusory self-touch was specific to the fact that hands crossed the body midline or whether the increase was caused by crossing of the hands per se (without crossing the body midline). The illusory self-touch ratings significantly differed across the four conditions ($\chi^2(3) = 24.891$, $p < .0001$). Post-hoc analyses with adjusted α level of .0167 revealed that, again, illusory self-touch was reported as more intense when the applied tactile stimulation was synchronous (crossed over the midline: $M = 4.33$, $SD = 2.19$; crossed in lateralized hemispace: $M = 4.60$, $SD = 2.09$) as compared to the asynchronous conditions (crossed over the midline: $M = 1.80$, $SD = 1.74$, $Z = -2.767$, $p = .006$, $r = .505$; crossed in lateralized hemispace: $M = 1.67$, $SD = 1.54$, $Z = -3.234$, $p = .001$, $r = .591$). Importantly, the intensity of illusory self-touch did not differ depending on where in peripersonal space the hands were crossed ($Z = -0.516$, $p = .606$, $r = .094$). The average ratings of the other two control items were low ($M < 1.5$, $SD < 1.85$) and did not significantly differ across the four conditions (Item 2: $\chi^2(3) = 0.953$, $p = .813$; Item 3: $\chi^2(3) = 0.395$, $p = .\ 941$).

The between-subject comparison of the self-touch illusory item ratings in the crossed in lateralized hemispace-synchronous condition with the ratings in the uncrossed – synchronous condition in Experiment 1 showed the crossed in lateralized hemispace condition to be significantly higher (Mann-Whitney U test: $Z = 2.242$, $p = .025$, $r = .423$). The ratings in this condition were also significantly higher from the unfamiliar-synchronous condition in Experiment 2 (Mann-Whitney U test: $Z = -2.346$, $p = .019$, $r = 0.436$).

The participants made larger pointing errors towards the rubber hand after they had been synchronously stroked compared to the conditions of asynchronous tactile stimulation ($F(1,14) = 12.07$, $p = .004$, $\eta_p^2 = 0.463$). The arm posture also significantly modulated the proprioceptive drift, which was larger in the conditions where arms were crossed over the body midline axis ($F(1,14) = 4.71$, $p = .048$, $\eta_p^2 = 0.252$). No interaction effect was found between synchrony of stimulation and the position of the crossed hands ($F(1,14) = 1.63$, $p = .222$, $\eta_p^2 = 0.105$) (see Figure 3).

Experiment 4: Effect of crossing in the visual RHI

When the standard visual RHI paradigm was administered, synchronous stroking in all three hand postures successfully induced illusory ownership (uncrossed hands: $M = 4.50$, $SD = 1.13$; crossed over midline: $M = 4.88$, $SD = 1.04$; crossed in lateralized hemispace: $M = 4.43$, $SD = 1.41$) that significantly differed from the control items (uncrossed hands: $M = 2.26$, $SD = 0.98$, $t(13) = 5.873$, $p = .0001$; crossed over midline: $M = 2.40$, $SD = 1.12$, $t(13) = 8.144$, $p < .0001$; crossed in lateralized hemispace: $M = 2.32$, $SD = 0.95$, $t(13) = 5.759$, $p < .0001$). However, no differences in mean ratings of any of the questions were found between different hand posture conditions (Q1 (*It seemed as if I were feeling the touch in the location where I saw the rubber hand touched*): $F(2,12) = 1.591$, $p = .244$, $\eta_p^2 = 0.210$; Q2 (*I felt as if the rubber hand were my hand*): $F(2,12) = 0.668$, $p = .531$, $\eta_p^2 = 0.100$; Q3 (*It seemed as though the touch I felt was caused by the experimenter touching the rubber hand*): $F(2,12) = 0.847$, $p = .453$, $\eta_p^2 = 0.124$; Q4 (*It felt as if my (real) hand were drifting towards the rubber hand*): $F(2,12) = 0.127$, $p = .882$, $\eta_p^2 = 0.021$; Q5 (*It seemed as if I might have more than one right hand or arm*): $F(2,12) = 0.469$, $p = .637$, $\eta_p^2 = 0.072$; Q6 (*It seemed as if the touch I was feeling came from somewhere between my own hand and the rubber hand*): $F(2,12) = 0.209$, $p = .815$, $\eta_p^2 = 0.034$; Q7 (*It felt as if my (real) hand were turning 'rubbery'*): $F(2,12) = 0.427$, $p = .662$, $\eta_p^2 = 0.066$; Q8 (*It appeared (visually) as if the rubber hand were drifting towards my hand*): $F(2,12) = 0.777$, $p = .481$, $\eta_p^2 = 0.115$; Q9 (*The rubber hand began to resemble my own (real) hand, in terms of shape, skin tone, freckles or some other visual feature*): $F(2,12) = 2.128$, $p = .162$, $\eta_p^2 = 0.262$).

There were no significant differences between the three conditions in the proprioceptive drift ($F(2,12) = 0.712$, $p = .510$, $\eta_p^2 = 0.106$). The results are shown in Figure 4.

Discussion

In four experiments we examined the effect of hand posture in the tactile and visual RHI. We show, for the first time, that crossing the hands, while synchronous tactile stimulation is given, increases illusory self-touch, i.e. the illusory sensation that one is touching oneself while one's own index finger physically touches a rubber hand. Follow-up experiments showed that the increase in

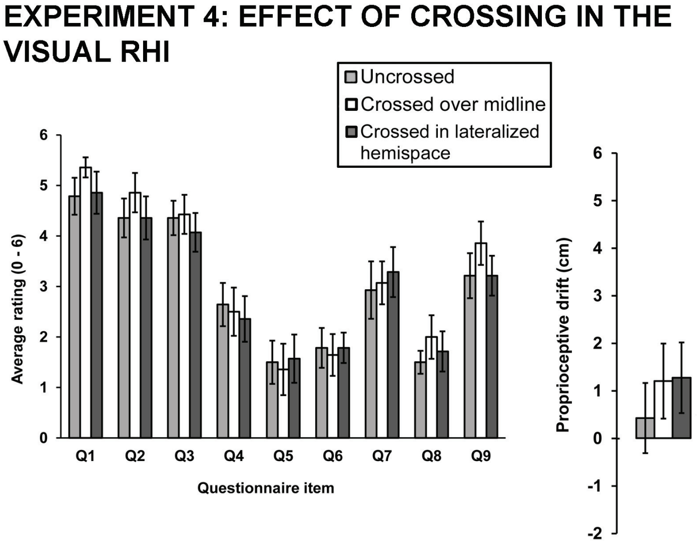

Figure 4. Questionnaire scores and proprioceptive drift results in the visual RHI. *Left panel* showing the average ratings of the questionnaire items for three different hand postures in the visual RHI paradigm (Experiment 4). The average ratings indicate that participants experienced the illusion (first three items). However, the posture manipulations did not affect the intensity of the illusion. The error bars represent the standard error of the mean. *Right panel* showing average proprioceptive drift measures in the visual RHI paradigm (Experiment 4) for the three hand postures. The differences between the three conditions did not reach the level of significance. The error bars represent the standard error of the mean.
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the illusion strength was not related to unfamiliar hand position (Experiment 2) and that illusory self-touch was equally strong regardless of where in the peripersonal space the hands were crossed (Experiment 3). These effects were evident from subjective reports, i.e. the questionnaire data, but not from proprioceptive judgments which were not modulated by crossing the hands. Finally, in contrast to the illusion increase in the tactile RHI, the crossed hand postures did not alter illusory hand ownership or proprioceptive judgments in the visual RHI (Experiment 4). Showing that the rubber hand illusion can be induced by manipulating tactile and proprioceptive input and its timing, the present data not only demonstrate that illusory self-touch can be induced by crossing the hands, but importantly, that this posture is associated with a stronger illusion.

To accurately localize a tactile event, tactile information coded within the somatotopic (skin surface anchored) coordinates is combined with proprioceptive and visual signals in a multisensory representation of the body [8,17,54,55]. These hand representations are constantly updated as we move by available multisensory information, amongst which the visual modality is an especially reliable source and therefore strongly biases the remapping process [50,51,56].

In the tactile version of the RHI paradigm, no visual information about the position of the hand in space is available, and therefore location of touch in external reference frame depends on the combination of proprioceptive and tactile cues. However, tactile and proprioceptive cues from the two hands are ambiguous: subjects feel their left hand being touched while at the same time their right hand touches a rubber hand. The synchrony between the two tactile inputs suggests that they refer to the same object, therefore inducing illusory sensation of touching one's own hand instead of the rubber hand. However, such perceptual solution raises a conflict between tactile and proprioceptive signals because, in terms of proprioceptive information, the two tactile signals coming from the hands cannot pertain to the same percept. As a consequence, the incongruent proprioceptive signals between the stroking and stroked hands are overridden by the more probable interpretation that two tactile events (spatially separated) are occurring at a single external location [57,58]. Consequently, the tactile-proprioceptive conflict is resolved in the experience of touching one's own hand, i.e. in illusory self-touch.

The new result from our study shows that postural manipulation i.e. crossing the hands has a boosting effect on the illusion. This finding diverges from previous studies, which have repeatedly shown that postural manipulations, other than having a hand in a default anatomical position and aligned with the rubber hand, lead to a decrease in the indices of the visual RHI [32,37,38]. A recent study also demonstrated that, in the tactile RHI, illusory self-touch decreases with increasing distance between the participant's stroked hand and the rubber hand and with increased incongruence in orientation between both hands [42].

The crossed hand related increase in the illusory self-touch can be explained by misalignment of somatotopic and external reference frames and consequently inadequate tactile-proprioceptive integration. In order to correctly localize the tactile event and act upon it, the somatotopic information is integrated with proprioceptive signals about the current position of hands and translated into a common, external space reference frame [25,28,45,59]. Mapping tactile stimuli in the external, multisensory peripersonal space is an automatic process, developed through early sensory experiences, driven primarily by vision [60,61]. The brain has a default way to map tactile stimuli from the somatotopic coordinates of the hand to its respective ipsilateral hemifield in the peripersonal space [15,60]. As crossing the hands introduces a strong conflict between the somatotopic and external space coordinates, the tactile-proprioceptive integration and remapping of tactile stimuli into the external space are altered. The misalignment of proprioceptive and tactile reference frames induces re-weighting of the tactile and proprioceptive signals. Due to generally less reliable proprioceptive cues, the probability that two spatially separated but temporally matched tactile events are interpreted as occurring at a single external location during the tactile RHI increases. Consequently, the estimation of the hand position is recalibrated to match the resolution of the tactile-proprioceptive conflict. As a result, the illusory self-touch is experienced as stronger.

Previous evidence has shown deficits in tactile re-mapping when crossing the hands and a consequent loss of perceptual reliability of proprioceptive information. An example of the crossed hand related remapping impairment is the increased difficulty to mentally visualize an object when it is bimanually explored with crossed hands while being blindfolded [62]. Moreover, in the TOJ task, when a blindfolded participant judges the temporal order of two successive tactile stimuli applied to each hand, the performance accuracy drastically decreases when arms are crossed [15,25,63]. Shorter inter-stimuli intervals (<300 ms) even lead to subjective inversion of the temporal order [15]. The same crossing decrease in the TOJ performance has also been shown for crossed fingers [16]. The boosting effect of crossing hands in the tactile RHI can be related to the so-called Aristotle illusion. In this illusion, rubbing the external sides of two adjacent and crossed fingers with a spherical object produces a percept of touching two distinct objects [64]. In a similar manner, simultaneous tactile stimulation of the inner parts of crossed fingers induces a sensation of touching only one surface [65,66].

The role of the remapping process in the perception of the tactile rubber hand illusion is also supported by studies in congenitally blind people. For example, it has been shown that blind people have smaller crossed hand effects in TOJ task [60] and, moreover, they do not experience illusory self-touch in the tactile RHI [58]. As suggested, congenitally or early blind people do not automatically remap somatotopic information into the external frame of reference, which is dominated by vision, but they rather rely on internal, anatomically based or egocentric reference frames [60]. Hence, in their case the automatic remapping in the external reference frame does not interfere with the tactile localization - as compared to sighted persons who mostly rely on the common external frame of reference, dominated by vision. However, the performance of sighted persons on the TOJ task improves when they perform the task having their hands crossed behind their back, that is in the peripersonal space not defined by visual input [67].

An alternative explanation for the increase of illusory self-touch is that proprioceptive cues of crossed hands increase the likelihood of single sensory event perception. When the hands are crossed, the angles of the upper arms are rotated towards each other, which is the position usually adopted when the hands are actually in tactile contact, compared to the angle when hands are positioned in parallel. The probability of self-touch under everyday conditions is thus higher when the hands are crossed, due to proprioceptive cues from the position of the arms (see also [42]).

In Experiment 2 we showed that the unfamiliar hand posture itself did not lead to the same boosting effect on the illusion as the crossed posture did, and it also did not decrease the ratings of the illusion when compared to the uncrossed posture. Moreover, Experiment 3 revealed that not only crossing the hands over the midline, but also crossing them in one hemispace, increases the ratings of the self-touch illusion. First, these findings suggest that the remapping impairments and the consequent increase of illusion are specific to the crossed posture. Secondly, the findings question the interpretation of self-touch illusion by White and Aimola Davies [42], who argue that the proprioceptive cues (coming from the elbow and shoulder rotation) contribute to the likelihood of perceiving two tactile stimuli as a single sensory event. In the unfamiliar posture the participant's left angular rotation of the shoulder joint was enhanced, whereas the left shoulder joints' rotation remained relatively the same as in the uncrossed posture. The proprioceptive incongruence between the participant's left and right hand was even more accentuated in Experiment 3, where the right hand (being crossed over the left) was positioned at the most extreme side of the participant's left hemispace. According to the interpretation of White and Aimola Davies these proprioceptive cues originating from the unfamiliar and crossed in a lateralized hemispace postures should decrease if not abolish the illusion. Nevertheless, the two explanations are not necessarily exclusive. Because proprioceptive signals have large variance and low reliability compared to visual information (at least in the frontal peripersonal space) [32,49,68], the illusory self-touch is experienced as long as the hands occupy a relatively limited and overlapping spatial range. When the distance between the hands increases, which is signalled by proprioceptive cues, the likelihood to experience two tactile stimuli as a single sensory event dissipates. In the present study, the distance between the two crossed hands (or two tactile stimuli) remained unchanged, but as the tactile-proprioceptive integration was hindered due to crossing hands, the likelihood to perceive a single tactile event increased. However, it remains to be further explored how increasing spatial separation between the crossed hands affects the intensity of illusory self-touch.

Furthermore, the follow up experiment (Experiment 3) revealed that not only crossing the hands over the midline, but also crossing them on one side of space (hemispace), increases the ratings of the self-touch illusion. The conflict between the somatotopical and external spatial frames of reference does not pertain to the fact that the hands are in their opposite sides of space with respect to the body midline, but it seems rather that crossing the hands per se is sufficient for enhancing the illusory self-touch. This can be linked to abundant literature on the use of different reference frames (body part rather than midline centred) for mapping tactile stimuli in healthy subjects, right brain damage patients with neglect and non-human primates [46,47,69,70].

We also applied the proprioceptive judgment measure in our tactile RHI experiments. In previous studies on the tactile RHI, drift towards the rubber hand illusion was found to be greater after synchronous stroking [41,43,71]. We found a larger drift of synchronous tactile stimulation on the drift measure towards the rubber hand in Experiments 1 and 3 (and marginally in Experiment 2). However, the manipulation of hand posture did not influence proprioceptive judgments.

The absence of the posture manipulation effect on the proprioceptive drift can be due to the fact that the spatial separation between the receiving and administering hand was the same in the uncrossed and crossed postures. Also, as the hand drift is never complete (it ranges between 15–30% of the distance between the real and rubber hand [49]), there might exist an upper limit of the hand mislocalization, which might be reflected in our data. Our results could also be confounded by unbalanced male to female ratio across the experiments. In Experiment 2, we had a large majority of male subjects and in accordance with reported gender differences in proprioceptive sensitivity this may have affected our data; we note, however, that the existing findings on gender differences in proprioceptive abilities are rather sparse and inconsistent, as the superiority on the non-visual proprioceptive pointing tasks was evidenced for females [72] as well as for males [73]. Furthermore, we measured the felt location of the stroked hand, which was receiving the touch, but not the mislocalization of the stroking hand. A recent study on the tactile RHI found the proprioceptive drift of the stroking hand to be larger compared to the stroked hand, which is traditionally used for the measure of mislocalization [43]. Last, the absence of a postural modulation of the proprioceptive drift in Experiment 1 might be related to the sample size, it is possible that a larger sample size might have resulted in a significant crossed hands effect on proprioceptive mislocalization towards the rubber hand.

In Experiment 4 we investigated how crossing the hands influences the experience of illusory ownership and proprioceptive drift in the visual RHI. The participant's right hand was stroked in synchrony with the viewed rubber hand while his hands were uncrossed, crossed over his body midline or crossed in the right hemispace. Although the misalignments between the somatotopic and external reference frame were the same and the participant's hands were occluded from view in both the tactile and visual RHI versions, we found no additional effects of crossing the hands in the visual RHI. Our data suggest that visual capture of touch, due to high spatial resolution of visual information, provided a strong external space reference, into which the tactile stimulus was coded. By dominating the remapping process of tactile stimuli into the external reference frame, vision overrode the proprioceptive cues from actual hand position, so that the felt and seen locations of the tactile stimuli were matched.

When taking into account the existent studies on postural manipulations in the visual RHI, where observed illusory ownership decreased with larger visuo-proprioceptive mismatches between the real and rubber hand [32,37,38], our results might appear contradictory at first glance. However, importantly, although the position of the participant's arms varied throughout the three conditions, the handedness, orientation and distance between the participant's stroked and rubber hand was constant in all conditions. Although the reliance on the proprioceptive cues might be reduced due to the arms being crossed, the visuo-proprioceptive similarity between the hands themselves did not change. In this sense, the studies cannot be completely compared. However, recent findings by Cadieux, Whitworth and Shore [74] are relevant. Using the visual RHI paradigm, they showed that when hands were crossed over the midline, the proprioceptive drift, contrary to our findings, diminished as compared to uncrossed posture. They explain the reduction of proprioceptive drift as a consequence of impaired tactile, visual and proprioceptive signal integration due to crossed posture. However, it is not possible to compare results of Cadieux et al. with those from the present study, because they did not collect subjective questionnaire data and thus no information about how crossing the hands affected illusory hand ownership in their study is available.

In conclusion, the present study is the first to show that crossing the hands enhances illusory self-touch in the tactile RHI paradigm. The study also links the illusion to well-established knowledge of posture effects on proprioceptive coding. Crossing the hands is a powerful manipulation to maximise the misalignment of the somatotopic and external reference frames. As this postural manipulation induces strong tactile-proprioceptive conflict, it is observed as a deficit on certain tactile processing tasks, while in the context of the tactile RHI it leads to enhanced illusory self- touch. Crossing the hands implies re-weighting of tactile and proprioceptive signals, leading to enhanced probability that two, spatially separated, but temporally matched tactile stimuli are mapped to the same location in the peripersonal space, and thus perceived as self-touch.

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Author Contributions

Conceived and designed the experiments: PP GR OB. Performed the experiments: PP GR. Analyzed the data: PP. Wrote the paper: PP GR RS OB.

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3.4 VOLUNTARY SELF-TOUCH INCREASES BODY OWNERSHIP

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Voluntary self-touch increases body ownership

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Experimental manipulations of body ownership have indicated that multisensory integration is central to forming bodily self-representation. Voluntary self-touch is a unique multisensory situation involving corresponding motor, tactile and proprioceptive signals. Yet, even though self-touch is frequent in everyday life, its contribution to the formation of body ownership is not well understood. Here we investigated the role of voluntary self-touch in body ownership using a novel adaptation of the rubber hand illusion (RHI), in which a robotic system and virtual reality allowed participants self-touch of real and virtual hands. In the first experiment, active and passive self-touch were applied in the absence of visual feedback. In the second experiment, we tested the role of visual feedback in this bodily illusion. Finally, in the third experiment, we compared active and passive self-touch to the classical RHI in which the touch is administered by the experimenter. We hypothesized that active self-touch would increase ownership over the virtual hand through the addition of motor signals strengthening the bodily illusion. The results indicated that active self-touch elicited stronger illusory ownership compared to passive self-touch and sensory only stimulation, and show an important role for active self-touch in the formation of bodily self.

Keywords: sense of body ownership, sense of agency, self-touch, rubber hand illusion, multisensory integration, volition, robotics and haptic technology

INTRODUCTION

A fundamental aspect of the experience of the self is the sensation that we have a body (body ownership) and that we control the actions of that body (agency) (Merleau-Ponty, 1996; Gallagher, 2000; Jeannerod, 2003). Body ownership is based on the correspondence and integration of multisensory signals (e.g., Ehrsson et al., 2004; Blanke, 2012; Salomon et al., 2013b). Agency, the sense of control over one's own actions, is thought to rely on integration of efferent and afferent sensorimotor information (Blakemore and Frith, 2003; Haggard, 2005; David et al., 2008; Jeannerod, 2009). A particular and relevant case in which body ownership and self-generated action interact is self-touch. Self-touch is thought to engender a basic form of self-awareness (Gallagher and Meltzoff, 1996; Merleau-Ponty, 1996), and has been suggested to contribute to structural and conscious representations of the body (Dieguez et al., 2009; Schütz-Bosbach et al., 2009; Kammers et al., 2010; van Stralen et al., 2011; Blanke et al., 2014). Self-touch is an important cue for body ownership since it includes a multisensory correspondence between two simultaneous tactile inputs (e.g., the hand that is touching and the hand that is being touched) coupled with corresponding motor and proprioceptive signals. Self-touch thus uniquely specifies one's own body as distinct from other objects in the environment. Developmentally, discrimination of self-touch vs. external touch arises early in life. Indeed, it has been shown that infants can discriminate self-touch from external touch when they are only 24 h old (Rochat and Hespos, 1997) and self-touch has been suggested to be important for the development of the sense of self in infancy (Rochat, 1998). Investigation of self-touch revealed that self-generated action reduces the perceived intensity of the tactile stimulation occurring simultaneously with the action (Weiskrantz et al., 1971; Blakemore et al., 1998, 1999). These findings speak in favor of a predictive "forward model" in which the expected sensory consequences of self-generated action are attenuated in order to enhance perception of external events (Wolpert et al., 1995; Bays et al., 2006; Shergill et al., 2012). Other research has linked passive self-touch and body representation through an adapted version of the RHI paradigm ("Somatic RHI," Ehrsson et al., 2005). In the Somatic RHI, the experimenter uses one of the blindfolded subject's fingers to touch a fake hand while synchronously touching the participant's other hand. This causes the sensation that the subject is touching his own hand and is associated with the mislocalization of the subject's touched hand toward the position of the fake hand (Ehrsson et al., 2005; White et al., 2010; Davies et al., 2013; Pozeg et al., 2014). Previous studies have focused on passive self-touch, yet in real life self-touch is typically caused by voluntary movements and thus includes predictive efferent signals, which may have an important role in establishing bodily self-representation through sensorimotor correspondences. Two contrary predictions could be made regarding the effects of active self-touch on the RHI: First, as active self-touch is associated with an attenuation of subjective tactile intensity and neural activation though efferent signals (e.g., Bays et al., 2005; Shergill et al., 2012) one could expect a reduced illusion due to attenuation of the tactile signal. Contrarily, efferent signals may boost the illusion though the addition of sensorimotor correspondences binding the tactile feedback to the self.

Here, in three experiments, we tested the effects of active and passive self-touch on body ownership. We hypothesized that active self-touch would induce stronger illusory self-ownership in the somatic and visual versions of the RHI due to the addition of efferent signals providing additional sensorimotor correspondences. We employed both subjective measures of illusory self-touch and illusory self-ownership (Botvinick and Cohen, 1998; Ehrsson et al., 2005; Tsakiris and Haggard, 2005; Lenggenhager et al., 2007; Rohde et al., 2011; Kalckert and Ehrsson, 2012; Pozeg et al., 2014) as measured by questionnaires and objective measures of proprioceptive drift (Botvinick and Cohen, 1998; Tsakiris and Haggard, 2005; Costantini and Haggard, 2007; Lenggenhager et al., 2007; Kammers et al., 2009; Tsakiris, 2010) which are well-established measures of bodily illusions (but see Rohde et al., 2011). Across three experiments and two variants of the RHI we found that active self-touch enhanced the illusory ownership.

MATERIALS AND METHODS

Participants

Forty participants were recruited through an advertisement at The University of Tokyo and Tokyo Metropolitan University. All participants were healthy, right-handed, had normal or corrected to normal vision, normal touch perception and no history of neurological or psychiatric conditions as assessed by self-report. All experiments involved different groups of participants. All participants had no preliminary knowledge about the RHI and the purpose of the experiment and gave written informed consent before the beginning of the experiments. The experiments were approved by the Ethics Committee in School of Engineering; The University of Tokyo followed the ethical standards laid down in the Declaration of Helsinki. Participants were reimbursed for their participation in the experiment with 1000 JPY per hour.

Robotic Master-slave System and Virtual Reality

A robotic master-slave system (see **Figure 1A**) was used throughout all the experiments. The participants held the handle of a master robot with their right hands and manipulated it to interact with a virtual left hand (see **Figure 1B**). When the tip of the handle touched the virtual hand the master robot rendered a virtual stiffness at the participants' right hand based on the contact state. The movement of the master robot was sent to a slave robot, which applied a tactile stimulus to the participants' left hand in real time. Therefore, the participants could feel as if they were touching their own left hand.

A custom-made two-degrees-of-freedom (2-DOF) parallel-link robot was adopted as the slave robot. In the slave robot, two DC motors (RH-8D 6006, Harmonic Drive Systems), which had harmonic gear heads with 1/50 reduction ratio and optical encoders with 1000 ppr resolution, produced movement in the X and Z directions and sufficient contact force on the participants' hand. The DC motors were controlled by motor drivers (4-Q-DC Servoamplifier LSC 30/2, Maxon) based on command voltage from a multifunction data acquisition device (NI PCIe-6323, National Instruments) installed on a desktop computer. A plastic cap was attached to the tip of the slave robot so that the slave robot safely interacted with the participants' left hand. As for the master robot, we adopted a PHANToM Omni (Geomagic formally SensAble), which is a commercialized 3-DOF haptic device with a pen-type handle, because of its easy availability and good force-display function (maximum force: ∼3.3 N); a previous experiment confirmed that the pen-type handle is intuitive for the participants to apply stroking and tapping to a rubber hand (Hara et al., 2011). The position sensing function of the master robot (resolution: ∼0.055 mm) was employed to measure the proprioceptive drift (see **Figure 1C**). The master and slave robots were arranged in front of the participants so that the distance between the two robots was 200 mm (see **Figure 1A**).

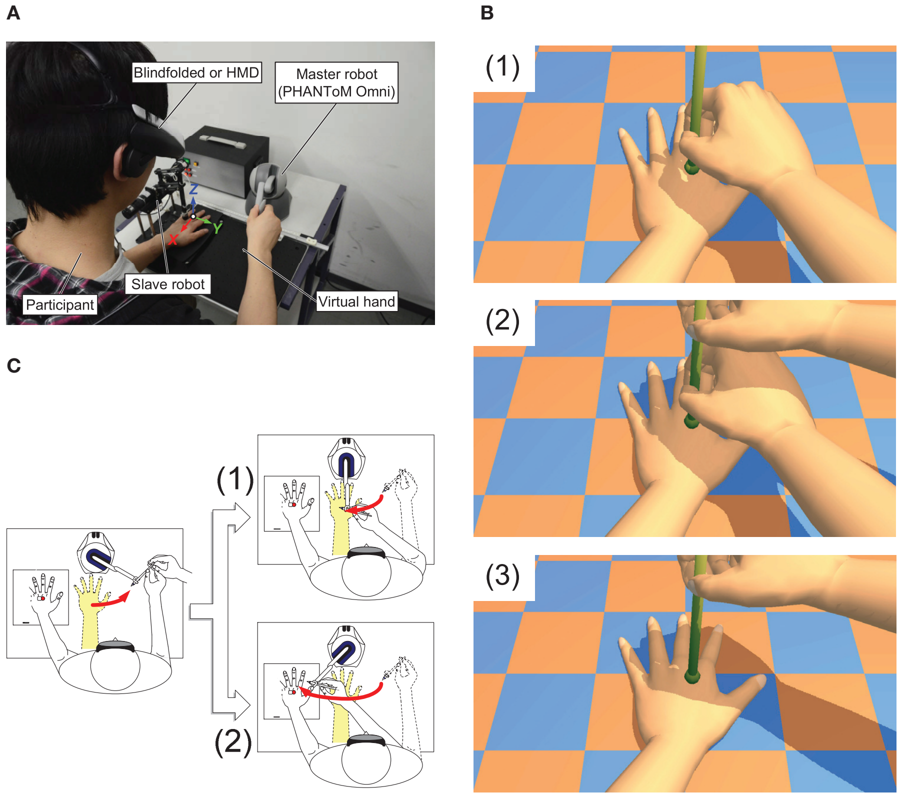

FIGURE 1 | Experimental setup and paradigm. (A) The robotic master-slave systems as well as the experimental setup are shown. The 2-DOF slave robot is controlled by the master robot to apply touch (tapping) on the back of participants' left hands in the Z (vertical) direction (see **Video 1**). When the slave robot contacted the participants' left hands, the master robot (PHANToM Omni) produces a virtual force based on a defined virtual dynamics of the virtual hand (mass: $M = 0.0$ kg; viscosity: $D = 0.0$ Ns/mm; stiffness: $K = 1.0$ N/mm) via an impedance controller. **(B)** A virtual scenario rendered with OpenGL and GLEW was projected on the HMD in a stereoscopic view. (1) In the active self-touch conditions, the participants' left and right hands were presented through the HMD. (2) In the passive self-touch conditions, an experimenter's right hand was also presented above the participants' right hands as to mimic the action of the experimenter. (3) In the classical RHI stimulation (Experiment 3 only), the participants' right hands were removed from view (2). The movements of virtual right hands were linked to the master robot and the virtual left hand never moved. The distance between the physical left hand and the tapping hand (either one of the participants or the experimenter) was always 200 mm. **(C)** In Experiments 1 and 2, the drifts of the participants' right hands were measured. First, an experimenter moved the pen-type handle of master robot connected to the participants' right hands 350 mm away from their left hands. (1) Before stimulation, the participants were asked to return the handle to the position where their right hands were, whereas they pointed to the tapping position after stimulation. In addition to the measurement of right hand drift, the drift of left hand was measured in Experiment 3. (2) In the measurement of left hand drift, the participants were asked to indicate the felt position of their left middle fingers with the handle before and after each experimental block.

Instead of the rubber hand, a virtual hand was constructed with a force display function of the PHANToM Omni based on the position where the slave robot contacted the participants' left hand. To increase the self-touch experience, we used an impedance controller to simulate stiffness of the virtual hand (1.0 N/mm). The position of the slave robot was controlled on the basis of the movement of the master robot. The robot control was performed with 1 ms sampling time (i.e., 1 kHz sampling rate). Thus, the intrinsic delay of the robotic system was around 1 ms.

A head mounted display (HMD: HMZ-T1, Sony, resolution: 1280 × 720 pixels in each screen) was employed to display 3D graphics of virtual experimental environment (virtual hands and a virtual stick) in stereoscopic view in Experiments 2 and 3 (see **Figure 1B**); the 3D graphics were rendered by using OpenGL and GLEW. The estimated intrinsic delay of the HMD is ~33 ms. The behavior of the virtual right hand was rendered synchronously or asynchronously with the movement of the master robot manipulated by the participants (active stimulations) or an experimenter (passive or classical stimulations). During all three experiments, white noise was presented to the participants through headphones on the HMD to mask the noise generated by the master and slave robots.

Dependent Measures

Proprioceptive Drift

We measured the effects of experimental manipulations on the change in proprioceptive sense of location (i.e., proprioceptive drift–PD) of participants' right, touch-administering (Experiments 1, 2, and 3) or left, touch-receiving hand (Experiment 3). The PD of the touch-administering hand was defined as a difference between the right hand location judgments before and after each experimental block. To obtain the pre-stimulation judgments, the experimenter lifted the participants' right hand, attached to the handle of the master robot, and positioned it ∼150 mm rightwards from the initial position. The participants were then asked to point with their right hand (attached to the handle) to the location of the initial position. Similarly, to obtain the post-stimulation judgments, the experimenter displaced participants' right hand ∼150 mm rightwards (or approximately 150 mm rightwards) from where they were tapping the virtual hand, and the participants were then asked to point to the location where they were touching the virtual hand during the experimental block (see **Figure 1C**). The pointed positions were measured by the position sensing function of the master device in a high precision. The PD for right hand was calculated as the difference between the pointed position before and after each experimental block.

When measuring the PD for the left, touch-receiving hand (Experiment 3), participants were asked before and after each experimental block to point with their right hand (attached to the handle of the master robot) to the felt position of their left middle finger (see **Figure 1C**). The PD was defined as the difference between the pre- and post-stimulation measures.

Illusion Questionnaire

A 6-item questionnaire was used to measure the strength of experienced self-touch illusion. The items were adapted from the somatic-RHI questionnaire. The first two items referred to the sense of illusory self-touch (Q1–"I felt like I was tapping my left hand") and the sense of agency (Q2–"The touch on my left hand matched the movements I made with my right hand"). The other items were unrelated to the bodily illusion and served as a control for suggestibility (Q3–"I felt like my left hand was becoming bigger"; Q4–"I couldn't feel my left hand"; Q5–"I felt as if I had more than one left hand"; Q6–"I felt my left hand was moving"). The participants were asked to designate on a 7-point Likert scale the strength of their agreement with each item (0 = "strongly disagree," 6 = "strongly agree"). An item, referring to the sense of illusory ownership over the virtual hand (Q7–"I felt as if the virtual hand was my own left hand"), was added to the questionnaire in Experiments 2 and 3.

Statistical Analysis

The questionnaire ratings for each item as well as proprioceptive drift measures in each condition were averaged across trials for each participant. Due to deviation from normal distribution (Shapiro-Wilk test for normality), the averaged questionnaire ratings of each item from all three experiments were first analyzed with the Friedman test, and if significant, they were followed up with pairwise comparisons, using the 2-tailed Wilcoxon's signed rank test. Three planned comparisons were made for the data sets in Experiments 1 and 2, where the ratings of the synchronous conditions were compared with their respective asynchronous pair, and those of the two synchronous, but different mode of tactile stimuli administration, with each other. The level of significance was corrected for multiple comparisons using the Bonferroni method, where corrected $\alpha = 0.05/3 = 0.0167$. The planned comparisons of the questionnaire data in Experiment 3 were made by first comparing the ratings between synchronous and asynchronous conditions; and then, among active-synchronous, passive-synchronous, and classical-synchronous conditions. The α-level was therefore corrected for six comparisons using the Bonferroni method, resulting in corrected $\alpha = 0.05/6 = 0.008$. The PDs of each experiment were analyzed with repeated measures analysis of variance (ANOVA) with two within-participants factors: *Stimulation type* and *Synchrony*. When the sphericity was violated in Experiment 3 (Mauchly's test of sphericity), the repeated measures ANOVA *p*-values were corrected by Greenhouse-Geisser's epsilon (Bolton et al., 2007) and if significant, followed-up with pairwise comparisons, using 2-tailed, paired-sample *t*-tests. We used the same planned pairwise comparisons and the correction of the α-level as for the questionnaire data. One-sample, two-tailed *t*-test was used to verify whether the PDs significantly differed from zero (i.e., no drift).

EXPERIMENTS AND RESULTS

Experiment 1: Active and Passive Somatic RHI

Participants

Thirteen participants (three females) participated in Experiment 1. Their age ranged between 20 and 39 years ($M = 27.0$, $SD = 6.5$).

Experimental Design and Procedure

In Experiment 1 we investigated the effect of active (self-administered) stimulation on the sense of illusory self-touch using the somatic version of the RHI (somatic-RHI) paradigm (Ehrsson et al., 2005; White et al., 2010). In a 2 × 2 repeated measures design we manipulated *Stimulation type* (active vs. passive self-touch) and *Synchrony* (synchronous vs. asynchronous tactile stimulation).

Prior to the experiment (i.e., training session), participants were instructed how to manipulate the robotic device and were explained the general procedure of the experiment. During the experiment, blindfolded participants sat in front of a table with their left hand (palm down) placed on the base of the slave robot while holding the pen-type handle of the master robot with their right hand. In the active self-touch conditions, the participants manipulated the handle to tap a virtual left hand, created with a force display function at the level of the master robot, rendered 200 mm to the right from the participants' left hand. In the passive self-touch conditions, the experimenter guided the participants' right hand with the handle of the master robot to touch (tap) the virtual hand. In the synchronous conditions, the actuated movements and received tactile feedback were synchronous, whereas in the asynchronous conditions, a constant 500 ms delay was applied to the movement of the slave robot (Blanke et al., 2014), resulting in delayed tactile contact between the slave robot and participants' left hand. The 500 ms delay used in the asynchronous is an established method for the asynchronous condition in bodily illusions (e.g., Shimada et al., 2005; Tsakiris et al., 2007; Shimada et al., 2009; Blanke et al., 2014). In each experimental block, the tapping stimulation lasted 30 s. Each of the four conditions was repeated five times and presented to the participants in a randomized order. At the end of each experimental block, we first recorded the PD measurements and then administered the illusion questionnaire.

Illusion Questionnaire Ratings

The analysis of the questionnaire data using the Friedman test showed statistically significant differences between the conditions on the ratings of the illusory self-touch [Q1: "I felt like I was touching my left hand"; $\chi^2(3) = 29.93$, $p < 0.001$]. The *post-hoc* planned comparison showed that stronger self-touch illusion was experienced when the tactile stimulation was synchronous as compared to asynchronous in the active [synchronous: $M = 4.37$, $SD = 1.48$; asynchronous: $M = 1.86$, $SD = 1.60$; $Z = -3.18$, $p = 0.001$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.62$] as well as in the passive conditions [synchronous: $M = 3.28$, $SD = 1.69$; asynchronous: $M = 1.58$, $SD = 1.64$; $Z = -3.11$, $p = 0.002$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.61$]. Importantly, the experience of illusory self-touch was stronger in the active-synchronous than in the passive-synchronous conditions [$Z = -2.80$, $p = 0.005$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.56$].

Statistically significant differences between the conditions were also found for the ratings of the sense of agency [Q2: "The touch on my left hand matched the movements I made with my right hand"; $\chi^2(3) = 33.52$, $p < 0.001$]. The planned *post-hoc* comparisons revealed that the participants experienced stronger sense of agency when the tactile stimulation was synchronous in the active [synchronous: $M = 5.26$, $SD = 0.84$; asynchronous: $M = 1.48$, $SD = 1.40$; $Z = -3.18$, $p = 0.001$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.62$] as well as in the passive conditions [synchronous: $M = 4.51$, $SD = 0.86$; asynchronous: $M = 1.12$, $SD = 1.19$; $Z = -3.18$, $p = 0.001$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.62$]. As predicted, during the synchronous stimulation, the sense of agency was enhanced in the active as compared to the passive condition [$Z = -2.84$, $p = 0.005$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.56$].

The ratings of the other four items were low ($M < 0.50$, $SD < 0.70$) and did not significantly differ across the four conditions [Q3: $\chi^2(3) = 0.82$, $p = 0.845$; Q4: $\chi^2(3) = 1.90$, $p = 0.593$; Q5: $\chi^2(3) = 4.16$, $p = 0.245$; Q6: $\chi^2(3) = 0.97$, $p = 0.809$].

Proprioceptive Drift of the Touch-administering Hand

Statistical analyses for proprioceptive drift of the touch-administering hand showed no significant main effects of *Stimulation type* [active: $M = 2.34$, $SD = 5.65$; passive: $M = 2.21$, $SD = 8.25$; $F_{(1,\,12)} = 0.00$, $p = 0.956$, $\eta^2 = 0.00$] and *Synchrony* [synchronous: $M = 3.21$, $SD = 6.84$; asynchronous: $M = 1.34$; $SD = 5.16$; $F_{(1,\,12)} = 2.69$, $p = 0.127$, $\eta^2 = 0.18$]. Statistically insignificant was also the interaction between the two factors [$F_{(1,\,12)} = 0.06$, $p = 0.813$, $\eta^2 = 0.01$]. Additionally, one-sample two-tailed *t*-tests showed that the mean PDs did not significantly differ from zero (i.e., no drift) in any of the experimental conditions [active-synchronous: $M = 3.47$, $SD = 8.11$; $t_{(12)} = 1.54$, $p = 0.149$; active-asynchronous: $M = 1.21$, $SD = 5.75$, $t_{(12)} = 0.76$, $p = 0.464$; passive-synchronous: $M = 2.95$, $SD = 10.10$, $t_{(12)} = 1.05$, $p = 0.313$; passive-asynchronous: $M = 1.47$, $SD = 7.13$, $t_{(12)} = 0.75$, $p = 0.470$].

Thus, the results of Experiment 1 (**Figure 2A**) indicated that synchronous active self-touch elicited stronger illusory self-touch than synchronous passive self-touch in the absence of visual feedback.

Experiment 2: Active and Passive Visual RHI

Participants

Fifteen participants (10 females) took part in Experiment 2. Their age ranged between 18 and 41 years ($M = 23.9$, $SD = 5.6$).

Experimental Design and Procedure

In Experiment 2, we investigated the effect of active (self-administered) stimulation on the strength of self-touch illusion and sense of illusory ownership over the virtual hand. Thus, we adapted and combined the somatic-RHI and classical RHI paradigms for the use in the virtual reality and robotic setting. As in Experiment 1, we manipulated *Stimulation type* and *Synchrony* in a 2 × 2 repeated measures design. We readapted the experimental procedure from Experiment 1 by adding visual cues of the virtual hands. Thus, a virtual scenario matching the experimental manipulation was projected through the HMD [see **Figure 1B** (1) for active conditions and **Figure 1B** (2) for passive conditions]. Similar to Experiment 1, each experimental block lasted 30 s, the order of the four conditions was randomized across the participants and each condition was repeated five times. The PD for the right, touch-administering hand was measured in the same manner as in Experiment 1 and the initial position of the participants' right hand matched the position of the virtual left hand projected onto the HMD. During the measurement of right hand localization, the virtual hands were not displayed on the HMD. At the end of each experimental block the participants also answered to the illusion questionnaire used in Experiment 1, which now also included an additional item referring to the sense of illusory ownership for the virtual hand (Q7–"I felt as if virtual hand was my own left hand").

Illusion Questionnaire Ratings

The ratings of the illusory self-touch significantly differed between the four conditions [Q1: "I felt like I was touching my left hand"; $\chi^2(3) = 31.71$, $p < 0.001$]. The planned pairwise comparisons showed that synchronous tactile stimulation increased the self-touch illusion in the active [synchronous: $M = 4.15$, $SD = 1.45$; asynchronous: $M = 2.56$, $SD = 1.78$; $Z = -2.75$, $p = 0.006$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.50$] as well as in the passive conditions [synchronous: $M = 2.82$, $SD = 1.52$; asynchronous: $M = 1.05$, $SD = 0.97$; $Z = -3.41$, $p = 0.001$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.62$]. During the synchronous stimulation, the participants reported stronger self-touch illusion when the tactile stimuli were actively applied to the hands [$Z = -3.33$, $p = 0.001$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.61$].

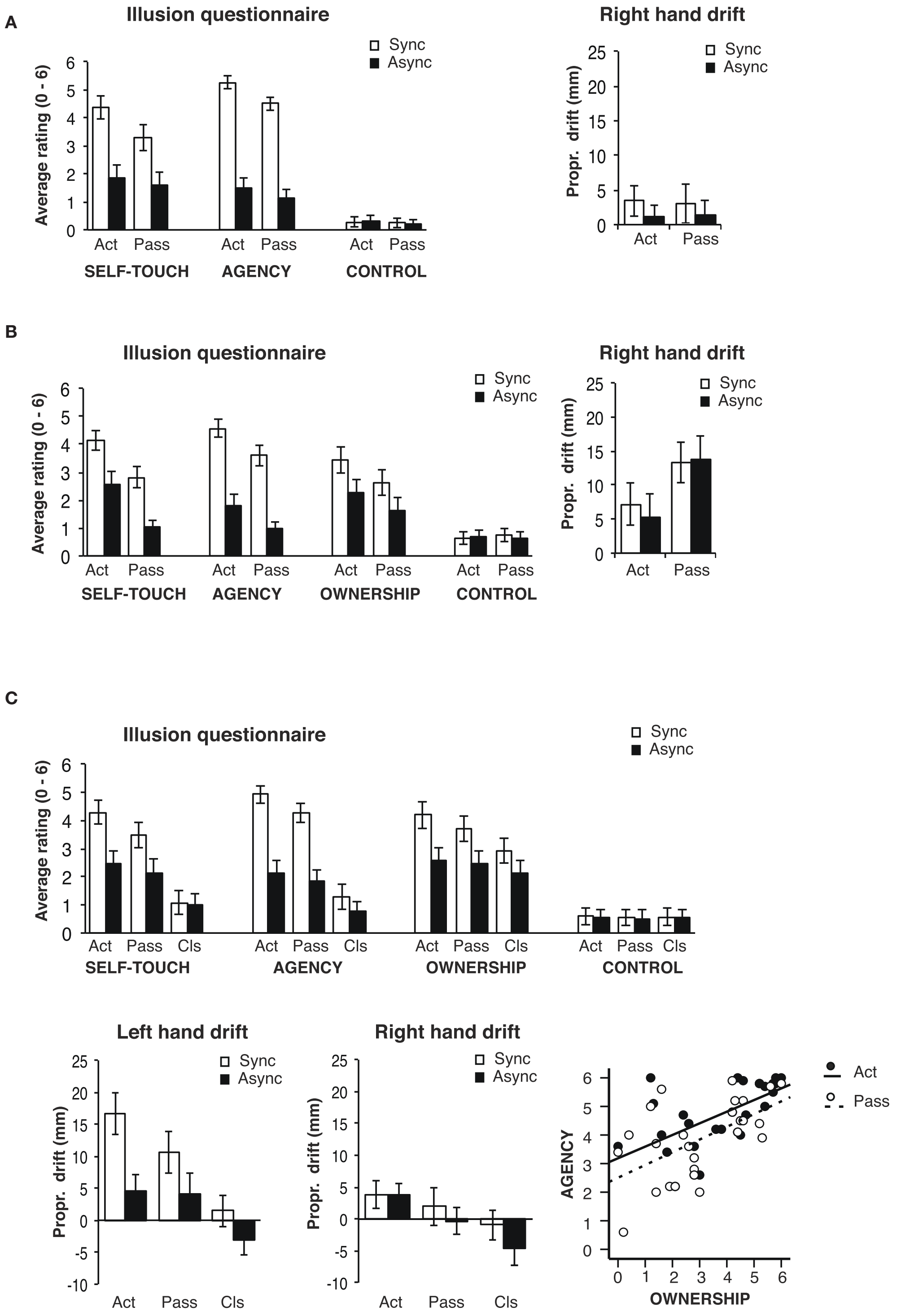

FIGURE 2 | **Mean questionnaire ratings and proprioceptive drifts. (A)** Mean questionnaire ratings and mean PDs for right hand in Experiment 1. The sense of illusory self-touch was enhanced in synchronous stimulation compared to asynchronous stimulation. Additionally, the participants reported stronger illusion when they

(Continued)

FIGURE 2 | Continued
actively touched the virtual hand and their own hands with the master-slave system. Neither synchrony nor stimulation type modulated the PD. **(B)** Mean questionnaire ratings and mean PDs for right hand in Experiment 2. In addition to the sense of illusory self-touch, the participants reported stronger illusory ownership over the virtual left hand with synchronous and active stimulation. Greater PD was found in the passive stimulation conditions. **(C)** Mean questionnaire ratings, PDs for both left and right hands in Experiment 3, and correlation between the sense of agency and sense of hand ownership for active-synchronous and passive-synchronous conditions. The illusory self-touch was induced in active and passive self-touch, and all the stimulation types allowed the participants to experience the illusory ownership over the virtual left hand. The experience of RHI became stronger in the order of active self-touch, passive self-touch, and classical stimulation. The PDs for right hand did not show any significance, but a greater PD for left hand was observed with synchronous stimulation in active self-touch. In the graphs, Act/Pass/Cls and Sync/Async mean active self-touch/passive self-touch/classical stimulation and synchronous/asynchronous, respectively.

The ratings of the sense of agency also significantly differed across the four conditions [Q2: "The touch on my left hand matched the movements I made with my right hand"; $\chi^2(3) = 33.41$, $p < 0.001$]. The follow-up planned pairwise comparisons showed that the sense of agency was rated stronger after the synchronous than the asynchronous tactile stimulation in the active [synchronous: $M = 4.56$, $SD = 1.26$; asynchronous: $M = 1.83$, $SD = 1.52$; $Z = -3.10$, $p = 0.002$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.57$] as well as in the passive conditions [synchronous: $M = 3.61$, $SD = 1.46$; asynchronous: $M = 0.97$, $SD = 0.83$; $Z = -3.41$, $p = 0.001$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.62$]. As we predicted, active tactile administration in the synchronous condition resulted in stronger sense of agency than in the passive-synchronous conditions [$Z = -3.19$, $p = 0.001$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.58$].

The Friedman test showed statistically significant differences in the ratings of illusory ownership over the virtual hand across the four conditions [Q7: "I felt as if virtual hand was my own left hand"; $\chi^2(3) = 20.90$, $p < 0.001$]. The planned *post-hoc* comparisons showed that the sense of illusory ownership was stronger when the tactile stimulation was synchronous in both, active [synchronous: $M = 3.43$, $SD = 1.77$; asynchronous: $M = 2.28$, $SD = 1.82$; $Z = -2.44$, $p = 0.015$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.44$] and passive conditions [synchronous: $M = 2.62$, $SD = 1.73$; asynchronous: $M = 1.65$, $SD = 1.64$; $Z = -2.79$, $p = 0.005$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.50$]. Importantly, the active stimulation increased the illusory ownership of the virtual hand as compared to the passive stimulation in the synchronous conditions [$Z = -2.45$, $p = 0.014$, $\alpha(\text{corr.}) = 0.0167$, $r = 0.45$].

The ratings of the other four items were low ($M = 1.80$, $SD < 1.80$) and were not significantly modulated by the experimental conditions [Q3: $\chi^2(3) = 2.46$, $p = 0.482$; Q4: $\chi^2(3) = 0.80$, $p = 0.849$; Q5: $\chi^2(3) = 2.17$, $p = 0.538$; Q6: $\chi^2(3) = 0.19$, $p = 0.980$].

Proprioceptive Drift of the Touch-administering Hand

Statistical analyses showed a significant main effect of *Stimulation type* [active: $M = 6.26$, $SD = 10.49$; passive: $M = 13.52$, $SD = 11.65$; $F_{(1,\ 14)} = 15.28$, $p = 0.002$, $\eta^2 = 0.52$] but no significant main effect of *Synchrony* [synchronous: $M = 10.25$, $SD = 9.58$; asynchronous: $M = 9.52$, $SD = 12.61$; $F_{(1,\ 14)} = 0.13$, $p = 0.726$, $\eta^2 = 0.01$] and no significant interaction between these two factors [$F_{(1,\ 14)} = 0.26$, $p = 0.617$, $\eta^2 = 0.02$]. One-sample two-tailed t-tests revealed that the mean PDs significantly differed from zero in all experimental conditions [active-synchronous: $M = 7.19$, $SD = 11.89$; $t_{(14)} = 2.34$, $p = 0.035$; passive-synchronous: $M = 13.31$, $SD = 11.41$, $t_{(14)} = 4.52$, $p < 0.001$; passive-asynchronous: $M = 13.72$, $SD = 13.16$, $t_{(14)} = 4.04$, $p = 0.001$], except in one experimental condition [active-asynchronous: $M = 5.33$, $SD = 13.51$, $t_{(14)} = 1.53$, $p = 0.149$].

The results of Experiment 2 (**Figure 2B**) indicated that with visual feedback, synchronous active self-touch elicited stronger illusory self-touch and sense of ownership over the virtual hand than synchronous passive self-touch. No synchrony-related PD was found for the touch-administering hand.

Experiment 3: Comparison of Active, Passive, and Classical RHI

Participants

Twelve participants (six females) participated in Experiment 3. Their age ranged between 21 and 32 years ($M = 25.8$, $SD = 2.6$).

Experimental Design and Procedure

In Experiment 3, we directly compared the role of experimental factors investigated in Experiments 1 and 2 to the classical RHI condition (touch completely administrated by an experimenter). Thus, we used a 3 × 2 factorial design with the within-participants factors of *Stimulation type* (active self-stimulation, passive self-stimulation, and classical tactile stimulation) and *Synchrony* (synchronous vs. asynchronous). Importantly, in this last experiment, we measured the PDs for both right and left hands. During each experimental block, participants viewed an appropriate virtual scenario through the HMD (**Figure 1B**). Similar to Experiments 1 and 2, each experimental block lasted 30 s, and six conditions were randomly presented and repeated 10 times; this yielded a total of 60 experimental blocks. At the end of each experimental block, the participants responded to the same questionnaire used in Experiment 2. The measurement of right hand localization was performed as in Experiments 1 and 2, with the only difference that we asked the participants to localize the position in which they saw the experimenter's tapping in the classical RHI experimental blocks (as the participants never moved their hands). In Experiment 3, we additionally measured the drifts of participants' left hand. Thus, before and after the experimental manipulation, the participants were asked to move their right hand (attached to the handle of the master robot) so as to point to the felt position of their left middle fingers (see **Figure 1C**). Both the right and left drifts were measured in two measurement orders (i.e., first for right/left hand drifts and second for left/right hand drifts) in each experimental block.

Each measurement order was presented five times and was balanced across participants.

Illusion Questionnaire Ratings

We first investigated the effects of active and passive self-touch as well as the classical RHI (tactile stimulation administered by an experimenter) on subjective ratings (see **Figure 2C**). The Friedman test showed that the ratings of the illusory self-touch significantly differed between the experimental conditions [Q1: "I felt like I was touching my left hand" $\chi^2(5) = 50.09$, $p < 0.001$]. The planned pairwise comparisons revealed that the illusory self-touch was experienced significantly stronger in the active-synchronous ($M = 4.29$, $SD = 1.51$) than in the active-asynchronous conditions [$M = 2.47$, $SD = 1.55$; $Z = -3.06$, $p = 0.002$, $\alpha(\text{corr.}) = 0.008$, $r = 0.63$]. The ratings of illusory self-touch were also significantly higher in the passive-synchronous ($M = 3.48$, $SD = 1.54$) as compared to the passive-asynchronous condition [$M = 2.15$, $SD = 1.72$; $Z = -2.65$, $p = 0.008$, $\alpha(\text{corr.}) = 0.008$, $r = 0.53$]. As predicted, low scores and no difference in the self-touch ratings between synchronous ($M = 1.08$, $SD = 1.43$) and asynchronous stimulation ($M = 0.98$, $SD = 1.45$) were found in the classical RHI tactile stimulation [$Z = -0.42$, $p = 0.673$, $\alpha(\text{corr.}) = 0.008$, $r = 0.09$]. Moreover, the ratings of the illusory self-touch in the active-synchronous condition were significantly higher than the ratings in the passive-synchronous [$Z = -2.937$, $p = 0.003$, $\alpha(\text{corr.}) = 0.008$, $r = 0.60$] and classical-synchronous conditions [$Z = -3.062$, $p = 0.002$, $\alpha(\text{corr.}) = 0.008$, $r = 0.63$], and ratings in the passive-synchronous condition were significantly higher than the ratings in the classical-synchronous condition [$Z = -3.06$, $p = 0.002$, $\alpha(\text{corr.}) = 0.008$, $r = 0.62$].

Significant differences between the experimental conditions were also found for the ratings of the sense of agency [Q2: "The touch on my left hand matched the movements I made with my right hand"; $\chi^2(5) = 46.68$, $p < 0.001$]. The planned pairwise comparisons revealed that the sense of agency was experienced significantly stronger in the active-synchronous ($M = 4.92$, $SD = 1.07$) than in the active-asynchronous conditions [$M = 2.12$, $SD = 1.69$; $Z = -3.06$, $p = 0.002$, $\alpha(\text{corr.}) = 0.008$, $r = 0.62$]. Similarly, the passive-synchronous stimulation ($M = 4.24$, $SD = 1.18$) resulted in higher ratings than the passive-asynchronous stimulation [$M = 1.83$, $SD = 1.47$; $Z = -3.06$, $p = 0.002$, $\alpha(\text{corr.}) = 0.008$, $r = 0.62$], whereas the synchrony of tapping did not affect the sense of agency in the classical RHI condition (synchronous: $M = 1.28$, $SD = 1.53$; asynchronous: $M = 0.75$, $SD = 1.29$; $Z = -1.95$, $p = 0.051$, $\alpha(\text{corr.}) = 0.008$, $r = 0.40$]. Moreover, the sense of agency was stronger in the active-synchronous than in the passive-synchronous ($Z = -2.65$, $p = 0.008$, $\alpha(\text{corr.}) = 0.008$, $r = 0.54$] and classical-synchronous conditions [$Z = -3.06$, $p = 0.002$, $\alpha(\text{corr.}) = 0.008$, $r = 0.62$]. The sense of agency was also rated stronger in the passive-synchronous as compared to the classical-synchronous condition [$Z = -3.06$, $p = 0.002$, $\alpha(\text{corr.}) = 0.008$, $r = 0.63$].

The Friedman test also detected statistically significant differences between the experimental manipulations in the ratings of illusory ownership [Q7: "I felt as if the virtual hand was my own left hand"; $\chi^2(5) = 44.56$, $p < 0.001$]. The planned *post-hoc* comparisons showed that the synchrony of tapping significantly increased the ratings of illusory ownership when the type of stimulation was active [active-synchronous: $M = 4.18$, $SD = 1.63$; active-asynchronous: $M = 2.58$, $SD = 1.61$; $Z = -3.06$, $p = 0.002$, $\alpha(\text{corr.}) = 0.008$, $r = 0.63$] as well as passive self-touch [passive-synchronous: $M = 3.72$, $SD = 1.60$; passive-asynchronous: $M = 2.44$, $SD = 1.66$; $Z = -2.98$, $p = 0.003$, $\alpha(\text{corr.}) = 0.008$, $r = 0.61$] but not in the classical RHI tactile stimulation [classical-synchronous: $M = 2.93$, $SD = 1.52$; classical-asynchronous: $M = 2.12$, $SD = 1.67$; $Z = -2.19$, $p = 0.028$, $\alpha(\text{corr.}) = 0.008$, $r = 0.45$]. When the stimulation was synchronous active self-touch resulted in higher ownership ratings than passive self-touch [$Z = -3.066$, $p = 0.002$, $\alpha(\text{corr.}) = 0.008$, $r = 0.63$] or touch administered by the experimenter in the classical RHI [$Z = -3.06$, $p = 0.002$, $\alpha(\text{corr.}) = 0.008$, $r = 0.63$]. The hand ownership ratings were also higher in the passive-synchronous as compared to classical-synchronous condition [$Z = -2.91$, $p = 0.004$, $\alpha(\text{corr.}) = 0.008$, $r = 0.59$].

No significant differences between the experimental conditions were found for the ratings of the other four questionnaire items [Q3: $\chi^2(5) = 5.37$, $p = 0.373$; Q4: $\chi^2(5) = 7.52$, $p = 0.185$; Q5: $\chi^2(5) = 9.88$, $p = 0.079$; Q6: $\chi^2(5) = 8.04$, $p = 0.154$].

Proprioceptive Drift of the Touch-administering Hand

The ANOVA showed that neither *Stimulation type* [active: $M = 4.54$, $SD = 7.89$; passive: $M = 3.28$, $SD = 4.53$; classical: $M = 1.55$, SD = 7.80; $F_{(1.26,\ 13.88)} = 0.56$, $p = 0.581$, $\eta^2 = 0.05$] nor *Synchrony* [synchronous: $M = 2.81$, $SD = 5.50$, asynchronous: $M = 3.43$, $SD = 4.35$; $F_{(1,\ 11)} = 0.13$; $p = 0.730$; $\eta^2 = 0.01$] significantly affected the PD of the participants' right (i.e., touch-administering) hand. Interaction between *Stimulation type* and *Synchrony* was also not significant [$F_{(2,\ 22)} = 1.84$; $p = 0.183$; $\eta^2 = 0.14$].

Proprioceptive Drift of the Touch-receiving Hand

The analysis of the PD of the left, touch-receiving hand showed a statistically significant main effect of *Stimulation type* [active: $M = 10.57$, $SD = 8.66$, passive: $M = 7.40$, $SD = 7.84$, classical: $M = -0.77$, $SD = 5.97$; $F_{(2,\ 22)} = 6.60$, $p = 0.006$; $\chi^2 = 0.38$] and *Synchrony* [synchronous: $M = 9.54$, $SD = 6.52$, asynchronous: $M = 1.93$, $SD = 5.75$; $F_{(1,\ 11)} = 7.89$, $p = 0.017$; $\chi^2 = 0.42$] on the PD of the participants' left (i.e., touch-receiving) hand. The interaction between the two experimental manipulations was not statistically significant [$F_{(2,\ 22)} = 1.59$; $p = 0.23$; $\chi^2 = 0.13$]. A *post-hoc* analysis of planned comparisons using a paired-sample two-tailed *t*-test showed that the PD after active and synchronous self-touch (active-synchronous: $M = 16.56$, $SD = 11.27$) was significantly larger than the PD after the active and asynchronous self-touch [active-asynchronous: $M = 4.57$, $SD = 8.58$, $t_{(11)} = 4.13$, $p = 0.002$, $\alpha(\text{corr.}) = 0.008$, $r = 0.78$] and larger than the PD after the synchronous tactile stimulation in the classical RHI [classical-synchronous: $M = 1.45$, $SD = 8.47$; $t_{(11)} = 4.48$, $p = 0.001$, $\alpha(\text{corr.}) = 0.008$, $r = 0.80$]. The other planned comparisons did not yield statistically significant differences (all $p > 0.008$).

Correlation between the Sense of Agency and Hand Ownership

In order to investigate the strength of the relationship between the sense of agency and hand ownership, we combined and correlated the ratings of the sense of agency (Q2) and illusory hand ownership (Q7) in the synchronous tactile stimulation from Experiments 2 and 3. The analysis revealed a strong positive relationship when the type of the tactile stimulation was active [Pearson's $r_{(27)} = 0.597$, $p = 0.001$, $\alpha(\text{corr.}) = 0.025$] as well as when it was passive [Pearson's $r_{(27)} = 0.569$, $p = 0.002$, $\alpha(\text{corr.}) = 0.025$].

DISCUSSION

Illusory Self-touch and Illusory Ownership

The present experiments investigated the induction of the well-established RHI, using active self-touch. We used a novel adaptation of the RHI employing a robotic master-slave system, which allowed participants to induce the tactile stimulation actively, thus introducing movement related efferent information to the illusion. Collectively, the results showed three main findings: First, active self-touch compared to passive self-touch increased subjective scores of illusory self-touch (Experiments 1 and 2) and also of illusory ownership (Experiment 2) in the somatic and visual versions of the RHI. Second, both active and passive self-touch increased illusory ownership of the virtual hand compared to the classical tactile only induction of the RHI (Experiment 3). Finally, proprioceptive drift, an objective measure of illusory body ownership was found only for the touch-receiving hand (Experiment 3) and was larger for active self-touch compared to the classical tactile RHI condition.

Agency and Illusory Ownership

While body ownership has classically been related to multisensory integration of passive sensory signals (Botvinick and Cohen, 1998; Ehrsson et al., 2005; Tsakiris and Haggard, 2005; Blanke, 2012) recent research has shown that sensorimotor correlations based on efferent signals provide important information for body ownership (Dummer et al., 2009; Kammers et al., 2009; Kalckert and Ehrsson, 2012; Suzuki et al., 2013), suggesting a role of motor signals in the formation of body representations. Experiments using matching visuo-motor stimulations have shown that these induce sensations of body ownership for limbs as well as bodies (Sanchez-Vives et al., 2010; Walsh et al., 2011; Banakou et al., 2013; Rognini et al., 2013). Here we go beyond visuo-motor correlations to show that motor signals present in active self-touch increase illusory ownership of a hand with respect to passive self-touch (proprioceptive signals) and classical RHI (tactile only). This finding expands previous works showing that passive multisensory visuo-tactile integration induces illusory ownership (Botvinick and Cohen, 1998; Tsakiris and Haggard, 2005; Costantini and Haggard, 2007; Ionta et al., 2011; Salomon et al., 2013b) by showing that efferent motor information is integrated and enhances the illusion. From a theoretical perspective, this is in line with accounts suggesting that action and motor signals have an important role in the formation of the sense of bodily self (Knoblich, 2002; van den Bos and Jeannerod, 2002; Blakemore and Frith, 2003; Schütz-Bosbach et al., 2006; Tsakiris et al., 2006; Salomon et al., 2009, 2013a). Furthermore, these findings show that the efferent motor information is integrated with not only visual signals as in previous visuo-motor RHI studies (Dummer et al., 2009; Kammers et al., 2009; Sanchez-Vives et al., 2010; Kalckert and Ehrsson, 2012, 2014; Banakou et al., 2013; Banakou and Slater, 2014) but also afferent proprioceptive and tactile signals which are thought to be central to body ownership (Blanke, 2012; Palluel et al., 2012). We suggest that this increase in the subjective aspect of the illusion is due to the additional information provided by the efferent motor signals of self-authored movements. These signals bolstering correspondence between the afferent sensory inputs and the predicted sensory consequences of the self-generated action provide an important source of self-related information (Tsakiris et al., 2005, 2006; Rognini et al., 2013; Salomon et al., 2013a) which in turn affects the incorporation of the virtual hand to the self. Interestingly, previous studies of self-touch have shown that tactile signals associated with self-touch are suppressed both at the behavioral level (Blakemore et al., 2000) and in the brain (Blakemore et al., 1998; Bays et al., 2006; Dieguez et al., 2009; Shergill et al., 2012; Martuzzi et al., 2015). While this suppression of tactile perception may seem to suggest that self-touch should have lower impact on a tactile based bodily illusion, we advocate an opposing interpretation, namely that the same predictive models underlying the tactile attenuation are also responsible for the increase in illusory ownership. Recent theories have suggested an important role for predictive coding (Friston, 2010) in establishing a model of the self (Clark, 2013; Apps and Tsakiris, 2014). These theories propose that the self is constructed through a Bayesian computation minimizing the prediction errors (incongruences between predicted and incoming sensory signals). Here, the addition of efferent information through active self-touch introduces further predictive signals that, when matched with the tactile sensations, strengthen the illusion that the hand belongs to the self. The efferent information, which is related to self-authored movements, may allow a reduction of the prediction errors though the increased sensorimotor correspondences. Thus, the convergence of multiple signals may enhance the illusory ownership. This is supported by our data, which shows a hierarchy of illusory embodiment based on the availability of motor (active), proprioceptive (passive) or tactile only (classical RHI) conditions.

Mislocalization of the Hand

The RHI is typically associated with a mislocalization of the stimulated hand toward the fake hand, often termed "proprioceptive drift" (Botvinick and Cohen, 1998; Costantini and Haggard, 2007; but see Rohde et al., 2011; Davies et al., 2013). Our novel robotic setup allowed precise and well controlled measurements of proprioceptive drift. Recently it has been proposed that such proprioceptive drift may be also presented on the hand administering the tactile stroking in the somatic-RHI (White et al., 2011). Our results (Experiment 1) did not replicate these findings of drift on the touch-administering hand during the somatic-RHI. However, the two studies differed in several aspects relating to the measurement of the proprioceptive drift. It is possible that differences in the experimental setup (virtual hand here vs. rubber hand in White et al., 2011), duration of stimulation (30 s vs. 180 s) or the mode of measurement (pointing vs. visual perceptual judgments) may account for this difference. In Experiments 2 and 3 using a visual version of the RHI no synchrony-modulated proprioceptive drift was found for the touch-administering hand. In contrast, the results of Experiment 3 in which proprioceptive drift was measured for both the administering and stimulated hand show a synchrony-modulated difference for the active condition for the tapped hand. Critically, the drift of the touched hand in the active self-touch condition was larger than that elicited by the classical tactile RHI, mirroring the effects found in the subjective feeling of illusory ownership. The results of the proprioceptive drift, an implicit measure of body ownership, show that active self-touch induces a larger mislocalization of the hand compared to tactile stimulation alone, suggesting that such proprioceptive error may also be affected by efferent predictive signals. A similar result has also been recently found using active self-touch in the context of the Full Body Illusion where synchronous active touch caused changes in subjective experience (Hara et al., 2014) and a larger proprioceptive drift of the full body compared to asynchronous tactile feedback (Blanke et al., 2014).

CONCLUSION

In a series of three studies using a novel robotic setup we have shown that active self-touch induces higher illusory ownership over a virtual hand as measured by subjective explicit, as well as objective implicit measures. Higher illusory self-touch was induced for both somatic and visual variants of the RHI, indicating that it is not dependent on visual feedback. Extending the results of previous studies on active movements in shaping our sense of bodily self (Tsakiris et al., 2006; Dummer et al., 2009; Kammers et al., 2009; Kalckert and Ehrsson, 2012; Suzuki et al., 2013), our results highlight the role of the correspondence between efferent motor signals and afferent sensory inputs in building our sense of body ownership. Thus, self-touch may have a special role in the formation of our bodily self-representation.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2015.01509

Video 1 | Demo movie about active self-touch: 162293_Hara_Video1.WMV.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Part 3

3.5 NEUROLOGICALLY AND ROBOT-CONTROLLED INDUCTION OF AN APPARITION

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Report

Neurological and Robot-Controlled Induction of an Apparition

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Summary

Tales of ghosts, wraiths, and other apparitions have been reported in virtually all cultures. The strange sensation that somebody is nearby when no one is actually present and cannot be seen (feeling of a presence, FoP) is a fascinating feat of the human mind, and this apparition is often covered in the literature of divinity, occultism, and fiction. Although it is described by neurological and psychiatric patients [1, 2] and healthy individuals in different situations [1, 3, 4], it is not yet understood how the phenomenon is triggered by the brain. Here, we performed lesion analysis in neurological FoP patients, supported by an analysis of associated neurological deficits. Our data show that the FoP is an illusory own-body perception with well-defined characteristics that is associated with sensorimotor loss and caused by lesions in three distinct brain regions: temporoparietal, insular, and especially frontoparietal cortex. Based on these data and recent experimental advances of multisensory own-body illusions [5–9], we designed a master-slave robotic system that generated specific sensorimotor conflicts and enabled us to induce the FoP and related illusory own-body perceptions experimentally in normal participants. These data show that the illusion of feeling another person nearby is caused by misperceiving the source and identity of sensorimotor (tactile, proprioceptive, and motor) signals of one's own body. Our findings reveal the neural mechanisms of the FoP, highlight the subtle balance of brain mechanisms that generate the experience of "self" and "other," and advance the understanding of the brain mechanisms responsible for hallucinations in schizophrenia.

Results and Discussion

Descending with his brother from the summit of Nanga Parbat, one of the ten highest mountains in the world, Reinhold Messner felt a third climber "descending with us, keeping a regular distance, a little to my right and a few steps away from me, just outside my field of vision" [10]. Messner "could not see the figure" but "was certain there was someone there," sensing "his presence" [10]. This apparition, the sensation that somebody is nearby when no one is actually present, is called the feeling of a presence (FoP) and has been described during periods of physical exhaustion [1, 3, 4, 11, 12] and has influenced occult literature and fiction [13]. Although people do not see the "presence," they may describe its spatial location and frequently turn around or offer food to the invisible presence [14, 15]. Although the FoP has been described in psychiatric [1, 2, 15, 16] and neurological patients [2, 16], its neural origin is unknown. A single case report showed that electrical stimulation in temporoparietal cortex induces the FoP, suggesting that disturbed sensorimotor processing (tactile, proprioceptive, and motor cues) is important [17]. However, this has not been confirmed in other patients, and the significance of these findings for the FoP in healthy subjects is unclear.

Neurology and the FoP

We performed lesion analysis and analyzed the associated hallucinations and neurological symptoms in 12 FoP patients (Table 1; Figure S1 available online). The presence was felt in all cases in close proximity to and behind the patient's body ($p < 0.01$). The presence was lateralized ($p < 0.01$) in contralesional space ($p < 0.01$) and equally often in right or left hemispace (not significant, n.s.; Table 1). Sensorimotor deficits ($p < 0.01$) and the experience of illusory movements of the presence during movements of the patient (n.s.) were frequent symptoms (Supplemental Experimental Procedures). For lesion analysis, we used a multimodal imaging approach, relying on combined functional and structural neuroimaging data to determine anatomical regions of maximal lesion overlap [18–20]. This approach, which combined functional and structural lesion data, was necessary because many patients suffered from epilepsy, and in several patients, FoP was induced by electrical stimulation, and because the FoP is rare. Projecting all lesions onto the left hemisphere, lesion overlap analysis highlighted three cortical regions: insular cortex, frontoparietal cortex, and the temporoparietal cortex (Figure 1A). We next compared lesion extent within these three cortical regions between FoP patients and control patients matched for complex hallucinations, etiology, and sensorimotor deficits (Figure 1B; Supplemental Experimental Procedures): lesion extent did not differ between both groups in Brodmann area 22 ($p = 0.18$) and 48 ($p = 0.68$), whereas FoP patients had significantly larger lesions in Brodmann area 7 ($p = 0.01$). These results show that although FoP is associated with insular, temporoparietal, and frontoparietal lesions, only frontoparietal lesions (Brodmann area 7) were specifically associated with the FoP.

Robotically Induced Bodily Illusions

In order to study the FoP in healthy subjects, we designed a master-slave robotic system [21] and investigated sensorimotor signals and their role in inducing FoP experimentally by integrating our findings with principles from other body illusions [5] (informed consent was obtained, and all the studies

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Table 1. Clinical Data for FoP Group: Clinical Data Are Summarized for Each FoP Patient

Patient	Diagnosis/Etiology	Lesion	Lesion Analysis	Neurology/Neuropsychology	Semiology
FoP a	neurocystcercosis	frontoparietal cortex (R)	MRI	gait disturbance/mild executive deficits	presence of a person while walking, to his right, behind
FoP b	epilepsy, status post (s/p) ischemic stroke, vasculitis	occipitoparietal cortex, frontoparietal cortex (R)	MRI, EEG	left-sided sensorimotor deficit	presence behind left shoulder, a silhouette, like a shadow of the same proportions; echopraxia; unpleasant; most frequently perceived while walking
FoP c	epilepsy	frontoparietal cortex (L)	MRI, EEG, PET, SPECT, iEEG	right-sided weakness/ postictal aphasia	presence of a “black person” behind her, no lateralization, unpleasant
FoP d	epilepsy, s/p resection of capillary angioma in the left insula	insula, frontoparietal cortex (L)	MRI, EEG, PET, SPECT, cortical stimulation	right-sided numbness/ executive deficits	presence of a man, behind to her right, in peripersonal space, fear and anxiety
FoP e	intracerebral hematoma, ischemic stroke	temporal lobe, frontal lobe, parietal lobe, insula (R)	MRI	left-sided sensorimotor deficit/anosognosia, reduplicative paramnesia	presence of daughter about 50 cm behind, to the right
FoP f	epilepsy, cerebral histiocytosis	thalamocapsular-caudate region, insula (R)	MRI, EEG	left-sided dysmetria/left spatial neglect	presence of “a person’s black shadow” to her left, same position and posture as the patient, close family member
FoP g	epilepsy, s/p capsulolenticular haemorragic stroke	insula, capsulolenticular region (R)	MRI, EEG	right-sided paraesthesia and hemiparesis/neglect, apraxia	presence of four people in mostly left frontal space, family members
FoP h	epilepsy, hemiplegic migraine	insula, parietooccipital cortex (L)	MRI, EEG	right-sided paraesthesia and weakness/aphasia	presence of a person’s “shadow” to his right, behind
FoP i	epilepsy	mesial temporal lobe, anterior temporal lobe (L)	MRI, PET, SPECT, iEEG	normal/postictal aphasia	sensation of somebody’s presence, behind to the left, anxiety
FoP j	epilepsy, s/p resection of a left temporal dysplastic lesion	temporoparietal cortex (L)	MRI, EEG, PET, SPECT, cortical stimulation	normal/aphasia, anomia	presence of a male shadow, behind to the right, same position, echopraxia
FoP k	epilepsy	posterior temporal lobe (L)	MRI, cortical stimulation	normal/aphasia	presence behind to the right, strictly unilateral, unpleasant, no echopraxia
FoP l	epilepsy, intracerebral hematoma	temporoparietooccipital cortex (L)	MRI, EEG	right sided sensorimotor deficit/aphasia, paraphasia, agraphia, alexia	presence of a person (“shadow of a female person”), on her right side (20–30 cm), behind, while standing and walking, echopraxia

were conducted in conformity with the Declaration of Helsinki; Supplemental Experimental Procedures). We investigated whether the FoP is associated with illusory touch sensations (questionnaire) and mislocalization of the body ([20, 22]; Supplemental Experimental Procedures) (Figure 2A; Figure S2; Movie S1). While standing and blindfolded, participants moved their arms and thereby moved the master device (via their inserted right index fingers) in front of them. These movements were sent to the slave robot, which applied tactile stimuli in real time to the participants’ backs (Figure 2A; Movie S2) [7]. Participants moved the master robot for 3 min while they received tactile cues on their backs (by slave robot) and their right fingertips (by master robot; Movie S2). Stroking was applied either synchronously or asynchronously (500 ms delay), with or without somatosensory force feedback at the hand (2 × 2 factorial design).

During synchronous, but not asynchronous, stimulation, participants (study 2; Supplemental Experimental Procedures) experienced the sensation of touching themselves (self-touch), despite extending their arms in front of their bodies ($p < 0.01$; Figure 2B). Synchronous stimulation and stimulation with force feedback were further associated with a drift of the subject’s body toward the front position, where they felt their hands ($p < 0.05$; Figure 2C; Movie S2; Supplemental Experimental Procedures). Thus, sensorimotor signals from the fingertip (forward-extended arm) while a tactile cue is applied to the subject’s back induce the illusory feeling of touching one’s own back with one’s own finger (self-touch) and bias self-location toward the fingertip. These findings extend earlier illusions due to sensory conflicts between two hands [5] or between two hands and the nose [23] to an illusion between hand and trunk (see also [6, 7]).

Robotically Induced FoP

More interesting effects were observed during stronger sensorimotor conflicts; during asynchronous stimulation, participants showed a drift in self-location in the opposite, backward direction ($p < 0.01$) and reported higher other touch than self-touch. Moreover, during postcondition debriefing, five subjects reported to have experienced a FoP (Supplemental Experimental Procedures). In study 3 (Supplemental Experimental Procedures), we investigated whether we could induce the FoP experimentally, predicting that under asynchronous stimulation without somatosensory force feedback (fingertip), subjects would feel the presence of a person that is touching them, associated with a backward drift in self-location (toward the presence). Figure 3A shows that participants experienced being in the presence of another person in the asynchronous versus synchronous stimulation condition ($p < 0.01$) and experienced being touched by that invisible presence behind them ($p < 0.01$). Asynchronous stimulation induced a backward drift in self-location toward the position of the presence ($p < 0.05$; Figure 3B; Movie S3).

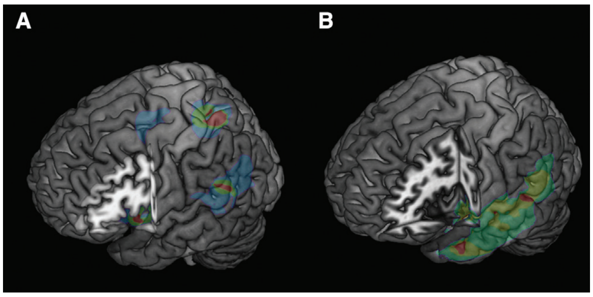

Figure 1. Lesion Analysis in Study 1

(A) Lesion overlap analysis for the FoP group revealed three regions where overlap was maximal. These regions were as follows: temporoparietal cortex (five patients; Brodmann area 22; Montreal Neurological Institute [MNI] x = 58, y = −51, z = 22), frontoparietal cortex (five patients; Brodmann area 7, MNI x = −32, y = −54, z = 62), and insula (five patients; Brodmann area 48; MNI x = −43, y = 8, z = −4). The color scale indicates the following: blue represents three patients, green represents four patients, and red represents five patients. Five patients had a right lesion, and seven patients had a left lesion; for analysis, all lesions were projected onto the left hemisphere.
(B) Maximal lesion overlap for the control group. The color scale indicates the following: green represents four patients, yellow represents five patients, and red represents six patients. Five control patients had a right lesion, and seven control patients had a left lesion; for analysis, all lesions were projected onto the left hemisphere.

To exclude that the FoP was caused by explicit questioning or related mechanisms, we designed a person numerosity task that tested implicitly the presence of another person close to the participant (study 4). While using the robot in synchronous and asynchronous stimulation, participants estimated the number of people that they felt were close to them in the testing room (the following question was asked: “how many people do you feel close to you?”). Data show that during the asynchronous (FoP-inducing) condition, participants judged a significantly higher number of people as being close to them (mean = 2.0) as compared to the synchronous condition (mean = 1.6; $p < 0.01$; Figure 3C).

Our neurological data reveal that the FoP is caused by focal brain lesions and that the FoP is most often experienced unilaterally, within peripersonal space behind the body, and associated with illusory own-body perceptions. FoP patients also show frequent somatosensory-motor deficits that were contralateral to the lesion on the same side as the presence. Compatible with the variability in lesion location across earlier clinical studies, we found that lesions associated with the FoP were focal but were linked to temporoparietal, frontoparietal, and insular cortex (of either hemisphere). Previous work showed that brain interference or lesions in FoP patients were in temporoparietal cortex [17] and frontoparietal cortex [2]. The present data also highlight that the FoP follows insular lesions and indicated lesion location with greater precision than previous work. Additional analysis in control patients (matched for complex hallucinations, etiology, and sensorimotor deficits) revealed that from the three lesion overlap zones, only the frontoparietal site was specifically associated with the FoP, highlighting the importance of the latter region in the FoP. Interestingly, temporoparietal cortex [20], insula [24], and frontoparietal cortex [5, 25] have been associated with bodily self-consciousness and are areas that integrate sensorimotor or multisensory bodily signals, as shown in human [26] and nonhuman primates [27, 28], compatible with the sensorimotor deficits we observed. The present findings highlight that the FoP is characterized by its own distinct phenomenology (compared to out-of-body experiences [OBEs], heautoscopy, and autoscopic hallucinations) and interference with frontoparietal cortex. All latter conditions have been linked to a single and hemisphere-specific lesion site [18, 20] and to disorders of multisensory integration that do not involve the sensorimotor system. OBEs are attributed to visuosomatosensory-vestibular disintegration [20, 29], heautoscopy is attributed to visuosomatosensory-interoceptive disintegration, and autoscopic hallucinations are attributed to visuosomatosensory disintegration [18, 30]. Instead, the present FoP data give most importance to abnormal integration of sensorimotor signals caused by frontoparietal lesions of either hemisphere. We note that these lesion overlap data have to be regarded with caution, as we included different types of brain lesions and included functional (intracranial electroencephalogram [EEG], cortical stimulation, and PET) and structural (MRI) lesion data. Moreover, our lesion overlap analysis also associated temporoparietal cortex and the insula with the FoP, but this was not corroborated by comparison with control patients. More work is needed to understand how these three regions differ in their involvement in the FoP.

The robotic data corroborate and apply our neurological findings to healthy subjects and show that sensorimotor conflicts using well-controlled bodily stimulations are sufficient to induce the FoP (albeit more weakly than in neurological patients). Based on clinical data and previous body illusion work [5, 7, 23], our robotic data show that the FoP can be induced when exposed to conflicting sensorimotor signals that are spatially and temporally incompatible with physical self-touch. Joining sensorimotor signals from forward-extended arms without force feedback at the fingertips (motor-proprioceptive cues), with delayed tactile feedback at the subjects' backs, was sufficient to induce the FoP. Under such stimulation, subjects reported being in the presence of another person behind them and being touched by that invisible presence. This was associated with a backward drift in self-location toward the presence and with elevated person numerosity judgments, corroborating our experiential findings behaviorally. The robotically induced FoP thus mimics the FoP in clinical populations and healthy subjects and is associated with abnormal perception of one's own body. These are major quantitative achievements because previous reports consisted of post hoc anecdotal accounts occurring far away from the research laboratory and because the FoP has never before been induced experimentally [1, 3, 4, 11, 12].

A prominent model for motor control and bodily experience posits that efferent copy signals from the sensorimotor system are used to make predictions about the sensory consequences of movement and that such integration is fundamental for normal bodily experience [8, 31]. Predicted sensory consequences based on motor commands are compared with the reafferent sensory inputs during motor execution. A match between the predicted sensory information and the actual sensory information is considered to be self-generated, whereas differences between predicted sensory consequences and the reafferent signals are indicative of the influence of an external object or another agent. Our master-slave robot generated a spatiotemporal mismatch between our participants' arm movements (motor-proprioceptive signals) and their sensory consequence (tactile feedback on their back), which was delayed and spatially incompatible with respect to the arm-related signals. This spatiotemporal conflict was resolved by our participants generating the illusory experience that the felt touch was not caused by themselves but by another person behind them who was touching their backs. This was revealed by subjective evidence, that is, a decrease in the reported feeling of touching one's own body, an increase in the feeling of being touched by somebody else, and an increase in feeling the presence of another person under asynchronous stimulation. Such reductions in self-touch and agency for one's actions have been reported before (visual-motor, audio-motor, and somatosensory-motor conflicts [31–34]). Our data are the first to induce such changes in association with the apparition or presence of another agent. Based on the present findings, earlier data using trunk stimulation [30], and theoretical considerations [35], we argue that the sensorimotor arm-trunk conflict in association with strong spatial incompatibility of self-touch induced the FoP.

In addition to explaining a fascinating phenomenon with a rich cultural history, the present data are also of relevance for the understanding of schizophrenic symptoms. Abnormal integration of sensorimotor signals and their cortical representations has been described in schizophrenic patients [36] and has been associated with positive hallucinatory and delusional symptoms [37, 38]. According to this view, positive schizophrenic symptoms, such as alien voices and delusions of control, are caused by central deficits in integrating predicted sensory consequences of own movements and the respective reafferent signals. As a consequence, schizophrenic patients under certain conditions may not perceive self-generated sounds and movements as such but may misperceive them as being generated by external agents (as in the experience of alien voices or control of own movements by others), and this is corroborated by behavioral and neuroimaging investigations [37, 39, 40]. The present data not only account for a loss of agency in such patients but also show that a conflict between proprioceptive-motor signals and tactile feedback at a physically impossible position induced the feeling of being in the presence of an alien agent and being touched by that invisible person. Furthering the mechanistic insight into the functional brain processes generating hallucinations and delusions, we show that simple sensorimotor conflicts induced, in healthy subjects, an experience that shares crucial aspects with positive, first-rank symptoms in schizophrenia, including the apparition of the alien agent [40, 41].

The FoP has fascinated mankind from time immemorial across all cultures, impacting the literature of divinity, occultism, and fiction. The phenomenon continues to fascinate humans today, as testified by several recent case collections [4] and documentaries [13]. Collectively, the present neuroimaging and robotics data provide a solid scientific explanation

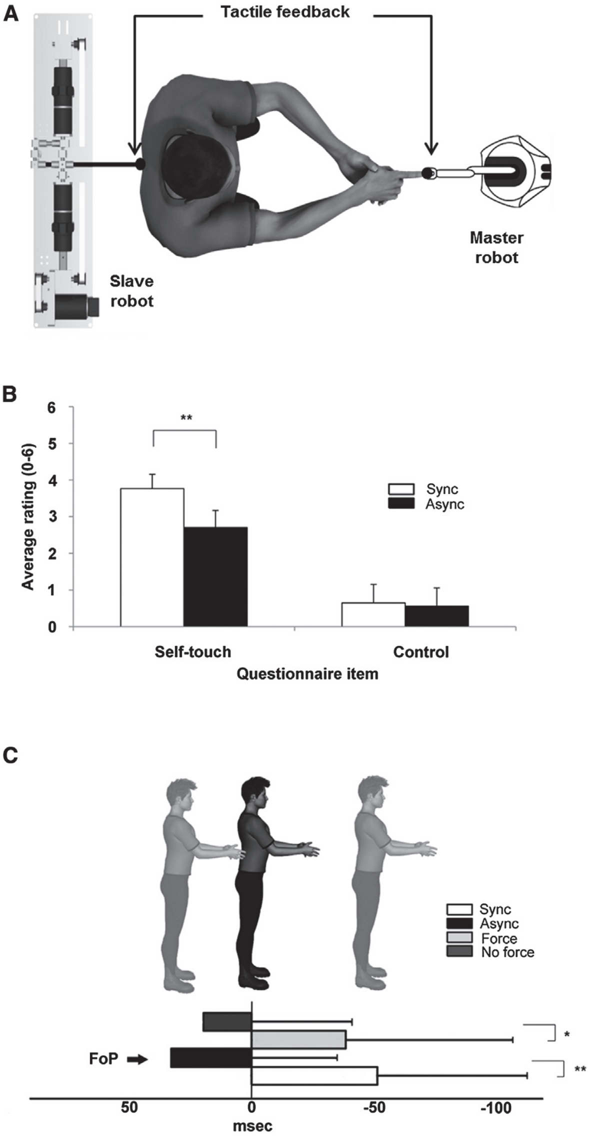

Figure 2. Master-Slave Robotic System and Tactile Full-Body Illusion in Study 2

(A) A schematic view of the master haptic interface (Phantom Omni; SensAbleTechnologies) and the slave robot are shown (see Movie S1; Figure S2; Supplemental Experimental Procedures). Position of the slave robot is controlled by the master robot, resulting in a total correspondence between the movements of the two devices (intrinsic delay < 1 ms). The participant moved the master robot via his right index finger (that was attached to the robot), which actuated the movements of the slave robot that applied touches to the participant's back. In order to test the impact of robotically controlled sensorimotor conflicts to induce changes in bodily self-consciousness, we tested the following four experimental conditions: (2 × 2 factorial design) (1) synchronous with force feedback, (2) asynchronous with force feedback, (3) synchronous with no force feedback, and (4) asynchronous with no force feedback. During the asynchronous conditions, the movements performed at the master device were delayed by 500 ms before being transmitted to the slave device (factor delay: synchronous or asynchronous). A "virtual back" in front of participants was created in order to have a mechanical stop (occurring synchronously or asynchronously) to the touch that the participant received on the back (factor force feedback: force or no force).

(B) Ratings for illusory touch and control questions are shown. Note that illusory self-touch is significantly larger in the synchronous versus asynchronous condition ($p < 0.01$) and also significantly larger than ratings of the control items ($p < 0.01$).

(C) Participants showed a drift in self-location toward the virtual back (toward the fingertip) that was larger during the synchronous than asynchronous conditions ($p < 0.01$) and was larger in the condition with versus without somatosensory force feedback to the participants' fingertip ($p < 0.05$) (Movie S2). Self-location was quantified using the mental ball throwing task, during which participants were asked to estimate (by pressing a button) the time that a ball they were holding in their hands would take to reach the wall if they were to throw it (Supplemental Experimental Procedures). The condition in which five subjects spontaneously noted a FoP is indicated with an arrow.

Error bars show the SEM.

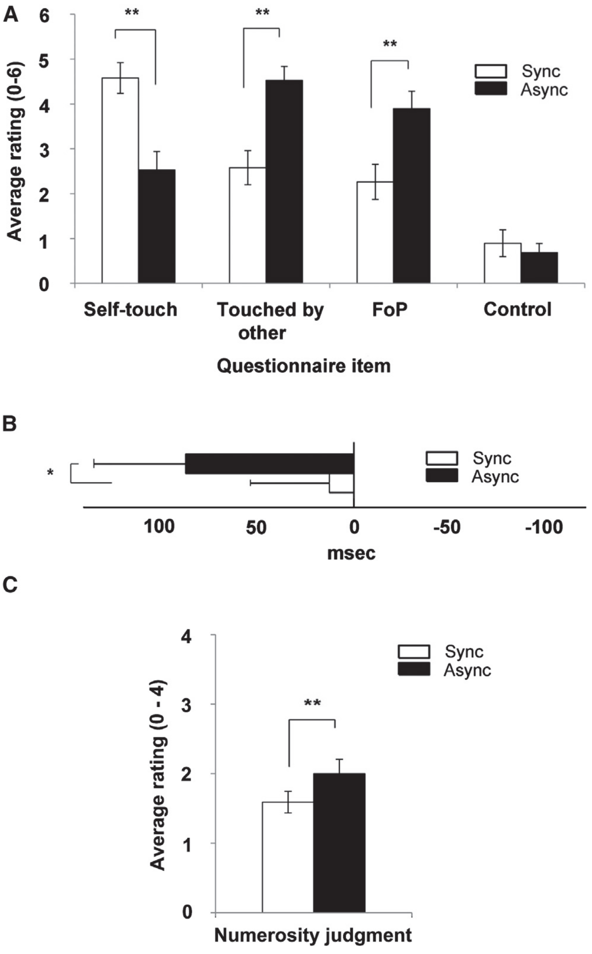

Figure 3. Robotically Induced FoP in Studies 3 and 4

(A) FoP questions, touched-by-other questions, illusory self-touch questions, and control questions are shown. As predicted, during asynchronous stimulation, participants experienced another person standing behind them (FoP; $p < 0.01$), touching them (touched by other; $p < 0.01$). As in study 2, synchronous stimulation induced illusory self-touch ($p < 0.01$).

(B) A significant difference in self-location was found between the asynchronous (backward direction, associated with FoP) and synchronous condition in study 3 ($p < 0.05$; Movie S3).

(C) Number of people (0–4) that participants judged as being close to them (the following question was asked: "how many people do you feel close to you?"; person numerosity task) during synchronous and asynchronous sensorimotor stimulation. As predicted, participants reported a significantly higher number of people during the FoP condition (asynchronous) than the synchronous condition ($p < 0.01$). Note that during the experiment, nobody was ever close to the participants.

Error bars show the SEM.

for the FoP and link a phenomenon that appears strange and complex at first sight to basic mechanisms of sensorimotor signal integration in a cortical network centering in frontoparietal cortex and to a prominent account of positive symptoms in schizophrenia. Apart from explaining a fascinating phenomenon and its potential clinical impact, the present data reveal the fine balance between the distributed cortical brain mechanisms in humans that generate the experience of "self" and "other," which, if distorted, give rise to the FoP.

Supplemental Information

Supplemental Information includes Supplemental Experimental Procedures, two figures, one table, and three movies and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2014.09.049.

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Supplemental Information

Neurological and Robot-Controlled Induction of an Apparition

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Supplemental Data

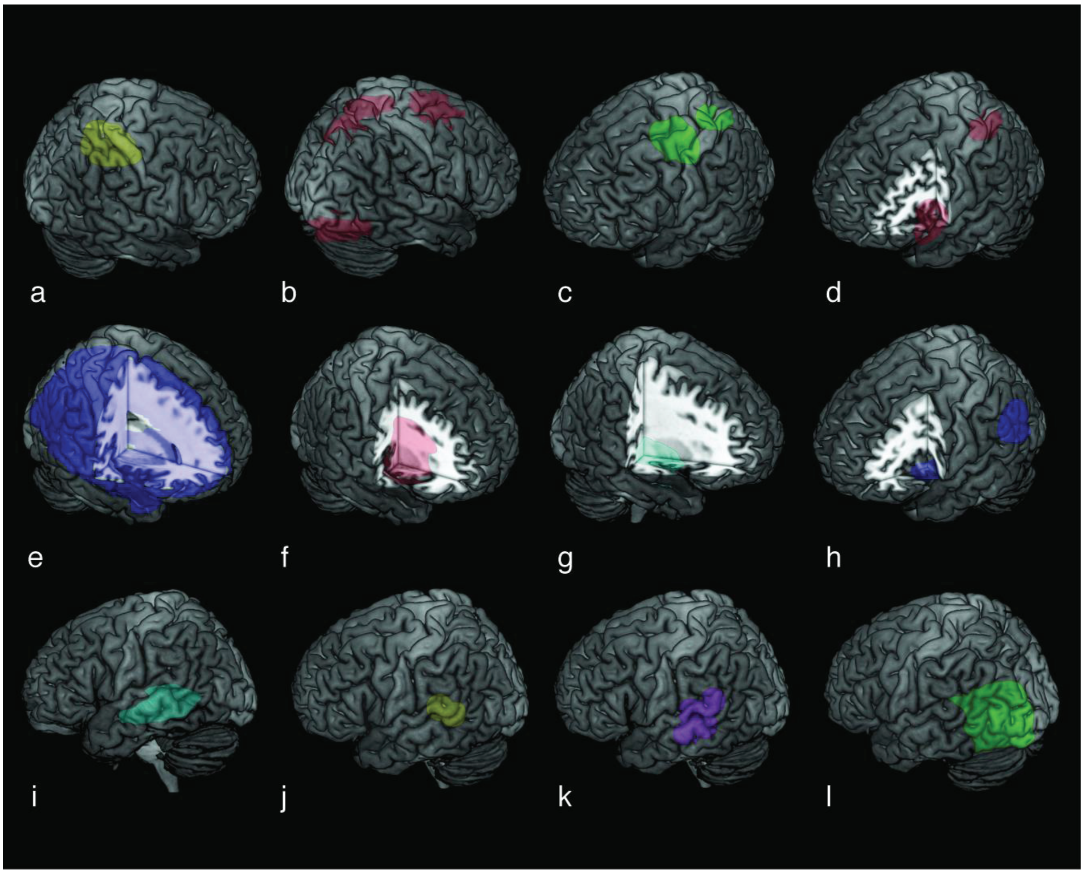

Figure S1. **Individual lesion data. Related to Figure 1.** The image shows the brain lesion separately for each of the 12 tested FoP-patients.

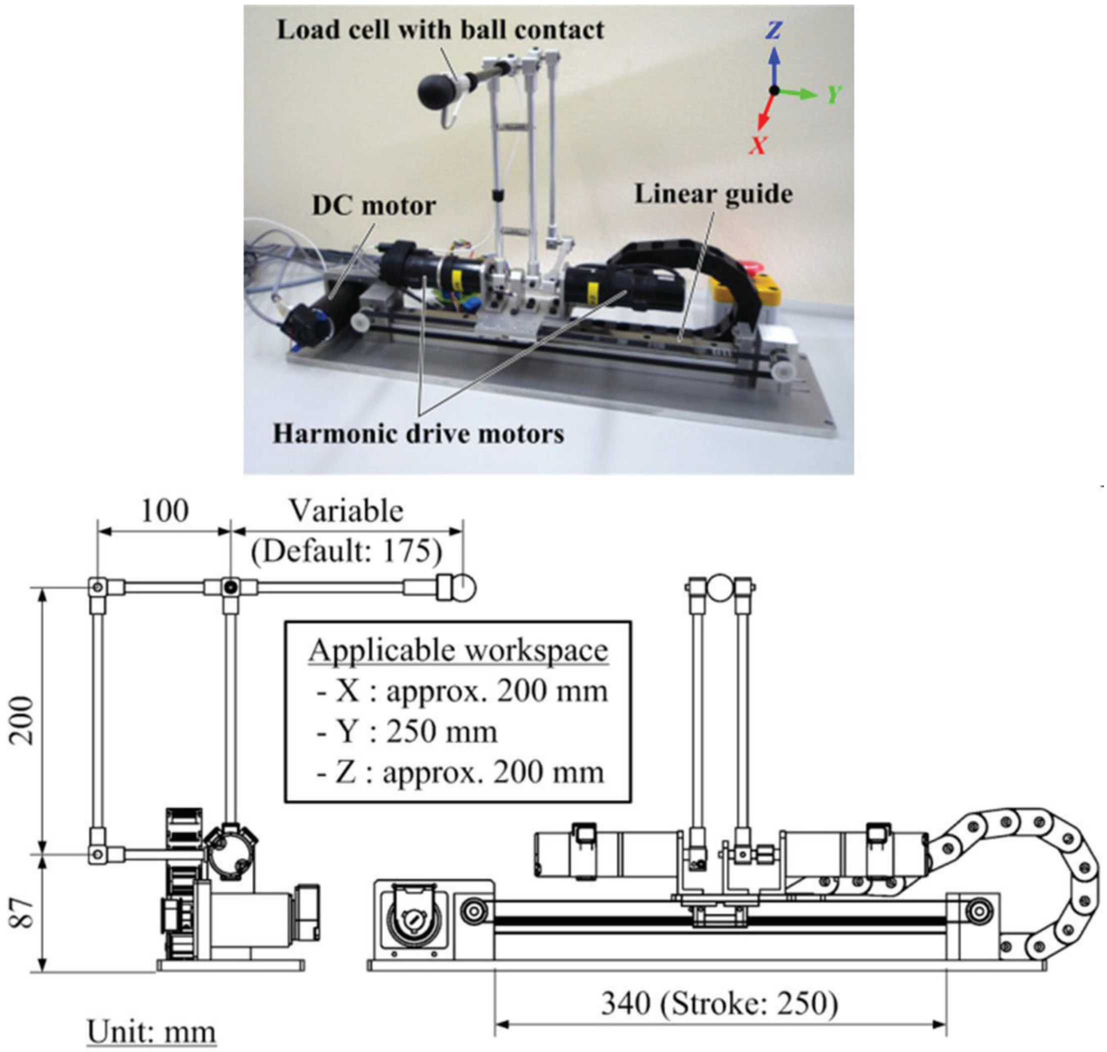

Figure S2. Bimanual master-slave robot. Related to Figure 2A. The slave device consists of two mechanisms: a belt-drive mechanism and a parallel-link mechanism. The belt-drive mechanism is made up of a belt linked to a direct-drive DC motor (RE 40, Maxon) moving a carrier on a linear guide allowing movements in the y (forward-backward) direction. The parallel-link mechanism is actuated through two harmonic drive motors (RH-8D 6006, Harmonic Drive Systems) and enables both tapping and stroking in x (right-left) and z (up-down) directions. These three motors equipped with optical encoders for positions sensing are connected to motor drivers (4-Q-DC Servoamplifier LSC 30/2 & ADS 50/5, Maxon) that receive the command voltages from a computer via PCI data acquisition cards (NI PCI-6221 & NI PCI-6014, National Instruments). The overall workspace of the slave device is 200mm in the x direction, 250mm in the y direction and 200mm in the z direction. A load cell (ELPFTIM-50N, Measurement Specialties) is attached on the tip of the slave device in order to measure contact force.

Patient	*Diagnosis/Etiology*	*Lesion*	*Lesion analysis*	*Neurology*
Control 1	Epilepsy, s/p ischemic stroke	Parietal cortex, R	MRI, EEG, PET	Facio-brachial left-sided sensory hemisyndrome, Somatoparaphrenia
Control 2	Epilepsy	Mesial temporal and insular cortex, L	MRI, SEEG	Burning sensation, whole body
Control 3	Epilepsy, cortical dysplasia	Temporal cortex, L	MRI, EEG, PET, SPECT	Right-sided hemiparesis, blurred vision
Control 4	Epilepsy, astrocytoma	Insular and temporal cortex, L	EEG, CT	Right-sided sensory hemisyndrome
Control 5	Ischemic lesion (Eclampsia)	Occipital lobe, R (L)	MRI	Cortical blindness, tetraparesis
Control 6	Epilepsy	Mesial temporal lobe and temporal cortex, R	MRI, EEG, PET, SPECT	Normal
Control 7	Subarachnoid bleeding (post operative lesion)	Parieto-temporal lobe, R	MRI	Left-sided hemiparesis
Control 8	Epilepsy, cortical dysplasia	Parieto-occipital cortex, L	MRI, EEG, SPECT	Normal
Control 9	Epilepsy, s/p cranio-cerebral injury	Parietal cortex, R	MRI, EEG	Left-sided hemiparesis
Control 10	Epilepsy, astrocytoma	Temporal cortex, L	MRI, Cortical stimulation	Right-sided hemiparesis
Control 11	Epilepsy, astrocytoma	Temporal cortex, L	MRI, EEG, PET, SPECT	Normal
Control 12	Epilepsy, cortical heterotopia	Temporo-parietal cortex, L	MRI, EEG, PET, SPECT	Normal

Table S1. Clinical data Control group. Clinical data are summarized for each Control patient.

Supplemental Experimental Procedures

Participants

12 patients with FoP and 12 patients that served as control group (see below; *Lesion analysis*) were recruited from the Department of Neurology at Geneva University Hospital and took part in study 1. A complete neurological examination and an extensive neuropsychological examination (oral and written language, visual gnosis, spatial functions, executive functions, memory) [S1] were carried out for each patient. A total of 17 healthy participants took part in study 2 (11 females; age range: 19-27 years; mean = 22.6; SD = 2.3 years). 21 new participants (11 females, age range: 19-24; mean = 21.1, SD = 1.9; two subjects were excluded from further analysis due to highly irregular stimulation patterns) took part in study 3 and additional 12 participants (7 females, age range: 19-27; mean = 23.6, SD = 2.6) in study 4. All participants were right-handed, had normal or corrected to normal vision and had no history of neurological or psychiatric conditions. Informed consent was obtained and the studies were conducted in conformity with the Declaration of Helsinki.

Methods

Electrophysiological recordings (study 1). Continuous long-term Video-EEG recordings with 29 scalp and two sphenoidal electrodes were available in 10 FoP patients (83%) and 9 Control patients (75%). Intracranial EEG as well as electrical cortical stimulation using subdural grid recordings (Ad-Tech, USA) were used in Patients c, d, i, j and k since non-invasive investigations did not allow us to define the epileptic focus and its anatomical dissociation from vital cortex [S2-S5]. Cortical stimulations were carried out (frequency of 50Hz; amplitude of 0.5 to 11mA, duration of 2 seconds) to localize motor, somatosensory, language and other functions.

Lesion analysis (study 1). In the FoP group, magnetic resonance imaging (MRI) was available in all patients (100%), positron emission tomography (PET) in 4 patients (33%), ictal and/or interictal single photon emission computed tomography (SPECT) in 4 patients (33%). In the control group, MRI was available in 11 patients (92%, in the remaining case CT was available), PET in 5 patients (42%), SPECT in 5 patients (42%). The epileptogenic region were determined using a multimodal imaging approach as described previously [18,20], relying on a combination of functional and structural neuroimaging data, as well as surface and intracranial EEG and data from electrical cortical stimulation. MRI brain scans were normalized to the smoothed T1 template using the standalone version of SPM8 (http://www.fil.ion.ucl.ac.uk/ spm/software/spm8) [S6]. As unified segmentation models give the most precise registration of structural images [S7], no cost-function masking was necessary. Functional imaging (PET, SPECT) was normalized using SPM8 and co-registered to the normalized MRI scans. Intracranial EEG was co-registered to the normalized MRI scans for each patient using the Cartool software developed by Denis Brunet (http://brainmapping.unige.ch/Cartool.htm). Lesions were subsequently traced manually slice by slice either on the individual normalized brain scans or on the T1 weighted images using MRIcron (http://www.sph.sc.edu/ comd/rorden/mricron) [19]. The later manual tracing on the template brain was only done when confidence could be achieved for matching corresponding slices between the lesioned brain and the template brain. In a few patients intracranial electrical stimulation and intracranial recordings were available and used to localize the epileptogenic zone and the eloquent cortex (patient c, d, j, i, k). In this group of patients the lesion site was defined as the location of those implanted electrodes (on the standard T1 template) where the seizure onset was found (plus an additional radius of 10 mm around the ictal onset zone). No patients with unclear lesion boundaries, generalized seizures or metallic artefacts were included into the analysis. Lesion volumes (volume of interest, VOI) were determined as the sum of all voxels compromising the traced lesion in all slices and were spatially smoothed using a 5mm full width at half maximum (FWHM) Gaussian Kernel and a threshold of 0.5. In order to illustrate maximal lesion overlap we used MRIcron [19] (http://www.sph.sc.edu/comd/rorden/mricron), thus establishing the anatomical sub regions of maximal lesion overlap by simple voxel-based lesion overlap analysis. All neuroimaging data were mirrored onto the left hemisphere in order to better illustrate the lesion overlap.

The 12 control patients have been selected to match the FoP group for: a) the presence of complex hallucinations; b) similar etiology, mainly epileptic; c) the presence of sensorimotor deficits. In order to match for sensorimotor deficits we chose from a group of 16 patients presenting complex hallucinations of focal origin all those patients that had sensorimotor deficits, (i.e. hemiplegia, hemiparesis or hemianesthesia; N = 8). To these 8 patients we added 4 more patients that were selected to match the FoP group for lesion laterality (i.e. 7 patients with left hemispheric and 5 with right hemispheric lesion). These 12 patients formed the control group. The two groups were matched for: 1) the presence of sensorimotor deficits: in 9 out of 12 cases in the FoP group and in 8 out of 12 cases in the control group; ($p>0.2$, two-tailed Fisher's exact test); 2) lesion laterality: both the FoP group and the control group were characterized by 7 patients with left and 5 with right lesion; and 3) neurological etiology: both the FoP group and the control group were characterized by 10 epileptic patients. In order to compare the extent of brain lesions between the two groups, we first computed the proportion of lesioned voxels in Brodmann areaa 7, 22 and 48, as defined by the Brodmann template implemented in MRICron. For each of the selected Brodmann region, we then compared the proportion of lesioned voxels between the two groups by means of non-parametric Mann-Whitney U test, with a significant p value set at $p<.016$, after Bonferroni correction for multiple comparisons (see [S8] for a similar approach).

Symptom analysis (study 1). Each case was analyzed by means of a semi-structured interview, which recorded detailed phenomenological information about the feeling of a presence (FoP) (location, character, color, identity, gender, age, sensorial manifestations, position, and posture). During the interview and report of the FoP, no patient had an impairment of consciousness (see also below, *Impairment of consciousness*). We also inquired about other hallucinations and body sensations, as well as emotional feelings during the experience. Phenomenological characteristics were analyzed using a Fisher's exact test (two-tailed) (Table 1).

Robot (study 2-3-4). The robotic system used in study 2 and 3 is composed of a commercial master haptic interface, the Phantom Omni (SensAble Technologies), and a three degree-of-freedom (DOF) slave robot [21] (see Figure S2). The slave device consists of two mechanisms: a belt-drive mechanism and a parallel-link mechanism. The belt-drive mechanism is made up of a belt linked to a direct-drive DC motor (RE 40, Maxon) moving a carrier on a linear guide allowing movements in the y (forward-backward) direction. The parallel-link mechanism is actuated through two harmonic drive motors (RH-8D 6006, Harmonic Drive Systems) and enables both tapping and stroking in x (right-left) and z (up-down) directions. These three motors equipped with optical encoders for positions sensing are connected to motor drivers (4-Q-DC Servoamplifier LSC 30/2 & ADS 50/5, Maxon) that receive the command voltages from a computer via PCI data acquisition cards (NI PCI-6221 & NI PCI-6014, National Instruments). The overall workspace of the slave device is 200mm in the x direction, 250mm in the y direction, and 200mm in the z direction.

A load cell (ELPFTIM-50N, Measurement Specialties) was attached to the tip of the slave device in order to measure contact force. This allowed us to introduce a compliance factor on the system preventing the slave device from applying instantaneous strong force to the participants, making the interaction safer and more realistic. The system was controlled through an application programmed in Visual C++ (Microsoft) at a sampling rate of 1 kHz. The latency related to information transfer delays and computational processing necessary for mapping the master device movements to the slave device movements (i.e. touching the back of the participants) was equal to 1ms (delay for the near-synchronous condition in experiments using movement, see below). Movements were always guided by the participants. The system had a bandwidth of approximately 2.5 Hz allowing a good synchrony (delay = 1ms) between the master and the slave even during rapid and abrupt changes in velocity and direction [21]. This allowed reducing the constraints on participants' movements.

Experimental design. We designed a master-slave robotic system that allowed us to investigate sensorimotor signals and their role in inducing FoP experimentally. The design of the robot was based on the sensorimotor findings from previous reports and the present patient study that we integrated with principles from other body illusions that have been tested in healthy subjects [5]. In one such body illusion the experimenter uses one of the blindfolded subject's fingers to stroke a fake hand (or another body part [5, 23]) while simultaneously touching the participant's other hand. This causes the sensation that the subject is touching his own hand and is associated with the mislocalization of the subject's touched hand toward the position of the fake hand [21]. Our robotic system extended such stimulations to full-body illusions and trunk stimulation [6, 7]; in particular, we investigated whether the FoP is associated with illusory touch sensations (questionnaire) and with evidence for mislocalization of the full body (with a previously used self-location measure [20, 22] (Figure 2A; Figure S2; Movie S1). Thus, in study 2 we first tested the following 4 different experimental conditions in a 2x2 factorial design: synchronous-force, asynchronous-force, synchronous-no-force, and asynchronous-no-force. During the asynchronous conditions the movements performed at the master device were delayed by 500 ms before being transmitted to the slave device (factor delay; synchronous, asynchronous). The delay was chosen based on previous work on hand ownership and agency with the present device [21]. In addition we manipulated somatosensory force feedback (force conditions) by generating a "virtual back" with a stiffness of 1.0 N/mm in front of the participant. This was created in order to have a mechanical stop occurring synchronously or asynchronously to the touch the participant received on the back (factor force feedback; synchronous; asynchronous). The value of stiffness was set to mimic the compliancy felt when touching a human body in order to increase the self-touch experience. Back stimulation was chosen because the FoP is in the large majority of previous cases and in those from study 1 reported as being located behind the subject. Based on self-touch manipulation concerning hands [5], we expected larger self-touch ratings in the synchronous rather than the asynchronous condition.

Since all the free reports of study 2 concerning the FoP occurred in asynchronous stimulation conditions, we next tested (study 3) whether asynchronous stimulation would induce the FoP in ratings. Most participants in study 2 reported FoP in the condition without force feedback. For this reason, and also to maximize sensorimotor conflicts, we chose to not provide force feedback in any of the conditions. The two conditions were therefore carried out in a mixed effects model design (see *Data analysis*): synchronous (SYNC) and asynchronous (ASYNC). SYNC and ASYNC conditions were the same as the synchronous-no-force and asynchronous -no-force conditions, respectively, in study 2. Again, we measured self-location with the MBT task and the subjective experiences with the questionnaire. Based on the free reports of study 2 we predicted higher ratings for the touched-by-other and FoP-question (see below, *Procedure*) in the asynchronous than in the synchronous condition. Similarly, we also expected participants showing a backwards drift (characterized by longer MBT RTs) during the asynchronous as compared to the synchronous condition.

Procedure (study 2-3-4). Prior to the experiment (training session) participants were instructed in how to use the robot and about the general procedure of the experiment.

Although they were explicitly told that the touch cue was administered by the slave robot during all experimental conditions, no mention of what type of master-slave mapping would occur was made (i.e., synchronous or asynchronous touch; with force feedback or without). The slave robot was placed behind their body, directly against the wall of the room and thus there was no space for a person to stand behind them.

When familiarizing with the robotic system, they were asked to perform tapping movements by inserting their right index finger into the master device (and holding the right hand with their left hand), while receiving the touches on their back by the slave device. As during the experimental condition, they were allowed to tap in any direction (up-down, left-right) resulting in touches applied to different parts of their back (within the workspace of 200x200mm, see *Apparatus*). Training lasted 1 minute and participants were not blindfolded (differently from the main experiment, see below).

In study 2-3, before the experiment, participants were given headphones and were blindfolded. Before the onset of the experiment we measured self-location using the mental ball throwing (MBT) procedure (baseline value; see *Self-location*). We then presented the four experimental conditions in randomized order (each lasting for 3 minutes). White noise was always presented over headphones to mask the mechanical noise produced by the moving slave device. At the end of each experimental condition, participants performed first the MBT procedure and then completed a 6-item questionnaire adapted from the tactile rubber hand illusion (tRHI) study by Ehrsson and colleagues [5]. One item was referring to illusory self-touch [i.e. the sensation that one is touching oneself ("I felt as if I was touching my body"; self-touch)] and another served as a contrast referring to the sensation of touching someone else's body ("I felt as if I was touching someone else's body"; other-touch). Two items were asked for the subjective displacement of one's self in front or behind one's own body ("I felt as if I was in front of my body" and "I felt as if I was behind my body"). Other items served as control items for suggestibility (i.e. “I felt as if I had no body”). Participants were asked to designate on a 7-point Likert scale, how strong they felt the sensation described by each item (0 = not at all, 3 = not certain, 6 = very strong). At the end of each experimental condition participants were also asked to freely report about the experiment. For study 3 we added two new items referring to the feeling of a presence: “I felt as if someone else was touching my body” (touched-by-other) and “I felt as if someone was standing behind my body.” (FoP).

In study 4, we asked our participants to judge the number of people (person numerosity task; “how many people do you feel close to you?”) that they felt to be present in the testing room, while they were using the sensorimotor robot in the synchronous and in the asynchronous conditions (in the same fashion as in study 3, while being blindfolded and hearing white noise). Before starting the experiment, the subjects had seen and heard four people discussing and standing in the testing room, and were told that during the experiment these people could have been or not in the room, close to them. At the beginning of the experiment, no other persons except the two experimenters were actually in the room, and, during the experimental manipulations, nobody was ever close to the participants. To clarify the meaning of “close”, an area of ~2m surrounding the robot was marked on the floor and was shown to the participants before the experiment started. At the beginning of the experimental procedure, participants were blindfolded and white noise was presented through headphones. The white noise intensity was tuned for each subject in order to have a complete acoustic isolation. Each block (synchronous or asynchronous robotic sensorimotor stimulation) lasted 2 minutes. In the first minute participants were only asked to self-administered the sensorimotor stimulation, whereas in the second minute they were asked to judge the number of people (from 0 to 4) they *felt* close to them for three times (every 20s). During each judgment trials, participants heard a first acoustic cue indicating to focus on the number of people they *felt* in close proximity, and 5s after another acoustic cue instructed them to verbally give the actual response of the person numerosity task. In total, participants performed 4 blocks per condition (and thus 12 trials per condition) in a randomized and counterbalanced order.

Self-location (study 2-3). In order to evaluate our participants' self-location, each participant was asked to perform an imagery task that we adapted from a similar task used in the supine position [20, S9]. In the training session, participants were asked to throw a few times a real ball (squeeze-ball, ~ 100g) towards the wall with their right hand. They were standing at the same distance to the wall (450 cm) as in the experimental session. Then, during the experiment they were asked to only imagine throwing the ball and to estimate the time the ball would need to "hit" the wall in front of them. Participants were asked to indicate the imagined onset of the ball throw by pressing a button on a response box with the thumb of their left hand, to keep it pressed, and to indicate the imagined impact of the ball with the wall by releasing the same button. The MBT task consisted of three consecutive trials, each of which was announced by an auditory cue delivered through the headphones and was recorded right after each experimental condition. A baseline measure (three trials) was also taken before the experiment.

Data analysis (study 2-3-4). As inferred with the Shapiro-Wilk test of normality most of the questionnaire data for studies 2-3 significantly deviated from normal distribution. We thus analyzed the data with a mixed effects model. The experimental factors (delay, force feedback and their interaction for study 2; delay: synchronous, asynchronous for study 3) were defined as fixed effects and "Subject" as a random effect, accounting for between-subjects variability. Self-location was calculated by subtracting the baseline value from the duration times in each trial of the experimental conditions. A mixed effect model was also used to analyze the MBT data, where "Trial" was additionally (together with "Subject") included in the model as a random effect, accounting for individual between-trial response variability. Similarly to study 2-3, the person numerosity judgments from study 4 were analyzed with mixed effect analysis, where delay (synchronous, asynchronous) was defined as fixed effect, and "Subject" and "Trial" as random effects. The post-hoc analyses for the questionnaire data were carried out using one-tailed Wilcoxon signed rank test. Significance was reported for p values smaller than 0.05.

Results

Study 1 (neurological patients, FoP group)

Phenomenology. Phenomenological characteristics are summarized for all patients in Table 1. FoP was described by all patients from the habitual visuo-spatial perspective (the physical body). The presence was described by all patients as being close to their body and within peripersonal space (most often within an arm's length from their body). In the large majority the presence was experienced as being behind and beside the patient (patients a-e, h-l). One patient reported the presence only beside (patient f) and one in front (patient g). All but one patient felt the presence only in one hemispace. Of these eleven patients, seven patients felt the presence strictly to their right, and four patients to their left. Altogether eight patients felt the presence contralateral to their lesion or zone of stimulation. Four patients (patients b,f, j, l) experienced the presence exactly in the same posture as their own (standing, sitting or supine). One patient described multiple simultaneous presences (patient g). All patients had repeated FoP and the presence was stereotypical and thus always had the same characters. Six patients (patients b,c,f,h,j,l) described the presence as a "shadow" or as a "black-person". In addition, the majority of the FoP patients reported that some of their movements and posture changes were experienced as illusory posture changes and movements of the presence (n=7; n.s.; Table 1). More specifically, three patients described the presence as active, especially while they were active as well (patients a,b,l). Echopraxia (i.e. the presence executes the same movements as the patient) and postural similarities where described by four patients (patients b, f, j, l). The clarity of the experience was described by all patients as high and vivid. Patients b, c, d, i, and k described the experience as fearful and as threatening. In all patients, details from the actual scene were integrated into the FoP, including the general location, objects in physical contact with the body (clothes, bed, chair), or people. No patient explicitly described the presence as a projection of his or her own body. Nevertheless, three patients described a close affinity between the presence and own-body (e.g. family member).

Simple visual manifestations occurred in patients h and j. Patients j and l experienced a unilateral hearing of a human voice and patient a described simple vocal as well as musical hallucinations. Patient a also described olfactory hallucinations. Regarding complex ictal hallucinations, patient d described the appearance of "little human figures" with colorful clothing. Patient h described an autoscopic hallucination in which he saw the upper part of himself. Regarding body-part illusions, patient b described a body distortion while looking into a mirror, patient f described the illusory feeling of holding an object in his right hand and a sensation of an alien hand; patient l described an illusion of dislocation of her contra-lateral arm and eye.

Etiology. Three patients (patients d, j, k) experienced FoP during cortical electrical stimulation (presurgical epilepsy evaluation), distant from the primary epileptic focus. In these patients, stimulation applied to specific sites reliably induced the FoP, whereas stimulation at other sites did not elicit the FoP. In seven patients (patients b, c, f, g, h, i, l) the FoP was related to complex partial seizures due to focal epilepsy. In one patient FoP was associated with an infectious disease (patient a) and in one patient related to stroke without evidence for epilepsy (patient e).

Impairment of consciousness. In four patients (patients c, h, i, l), FoP was associated with a mental state that was characterized by a partial impairment of consciousness due to complex partial seizures. This impairment of consciousness was only partial and of short duration as determined by the ictal and post-ictal clinical examination. The clinical evolution in these patients was characterized by quick recovery of full consciousness and the absence of secondary generalizations. The other patients did not show any impairment of consciousness associated with the FoP, but may have presented impairments of consciousness at different times that were not associated with the FoP, due to their neurological disease (i.e. epilepsy).

Neuropsychology. In six patients, the neuropsychological examination detected moderate to severe signs of aphasia, agraphia, alexia or apraxia. Moderate to severe spatial disturbances or visual agnosia were found in two patients. Mild verbal and visuo-spatial memory impairments were observed in one patient; deficits in executive functions, compatible with a frontal lobe disturbance, were found in two patients.

Study 2 (healthy subjects)

Questionnaire. Statistical analyses showed that the main effect of synchrony was significant (synchronous: M = 3.76, SD = 1.61, asynchronous: M = 2.71, SD = 1.92; F(1,48) = 12.81, p = .001), whereas providing force feedback to the performed movements did not modulate illusory self-touch (force: M = 3.29, SD = 1.80, no force: M = 3.18, SD = 1.74; F(1,48) = 0.158, p = .693). There was no interaction between force feedback and synchrony of stroking (F(1,48) = 2.529, p = .118). The ratings of illusory self-touch in the synchronous conditions were also significantly higher than the ratings of the control items (Wilcoxon signed rank test: all p < .01). Providing force feedback also led to increased ratings of other-touch (“I felt as if I was touching someone else’s body”) (force: M = 2.59, SD = 2.19, no force: M = 1.62, SD =

1.94; F(1,48) = 7.712, p = .008), irrespective of the synchrony of tactile feedback (synchronous: M = 1.97, SD = 2.08, asynchronous: M = 2.24, SD = 2.05; F(1,48) = 0.574, p = .453; interaction: F(1,48) = 0.177, p = .676). The average ratings of other four items were all low (less than 2.6) and did not significantly differ across the conditions (F(1,48) ≤ 3.100, all p > .05), with an exception of "I felt as if I was standing in front of my body" where synchronous stroking increased the described sensation (synchronous: M = 1.85, SD = 1.98, asynchronous: M = 1.35, SD = 1.62; F(1,48) = 4.240, p = .045). Of importance for the present study, during post-condition debriefing, five participants spontaneously reported having an illusion of a presence of another person, standing behind and touching them. This was noted by three participants after the asynchronous-no-force condition ("I felt someone is touching my back", "I felt I was touching nothing, and someone was touching me", "I felt like there was a loop: I am touching someone who then touches my back", and "I felt there was another person touching my back") and by two participants (one of whom had a similar feeling in both conditions) after the asynchronous-force condition ("I felt someone else was touching me" and "I felt as if somebody else was touching my back"). We note that FoP induction only occurred in the asynchronous conditions.

Self-location. Self-location based on the MBT task differed across the experimental conditions. Statistical analyses revealed a main effect of synchrony (F(1,150) = 11.171, p = .001) for self-location, with participants localizing themselves closer to the wall (in front) in synchronous as compared to the asynchronous conditions. We also observed a significant main effect of force feedback (F(1,150) = 5.323, p = .022). In the conditions with force feedback the participants showed self-location closer to the wall (in front) as compared to the conditions without any force feedback (see Figure 2C of the main text).

Feeling of a presence. We note again that in the five participants that freely reported a FoP, this only occurred in the asynchronous conditions. Inspection of their data showed that the

FoP was associated with low self-touch ratings [average rating in the asynchronous (force and no-force) conditions: 1.7] and associated with a drift in self-location towards a position behind the participants' body (RT difference from baseline was 171 ms in the asynchronous conditions and 82 ms in the synchronous conditions); note that a positive self-location value corresponds to a drift to a position behind the physical body of the participants).

Study 3 (healthy subjects)

Study 3 directly investigated whether the FoP (as spontaneously reported by five subjects during asynchronous conditions in Study 2) could be induced systematically.

Questionnaire. As in study 2, the experience of illusory self-touch was significantly stronger in the synchronous (M = 4.58, SD = 1.57) than the asynchronous condition (M = 2.52, SD = 1.89; F(1,36) = 13.175, p = .001). The average rating of illusory self-touch in the synchronous condition was also significantly higher than the ratings of the control items (all p < .01). Significant differences were also observed for the ratings of the "feeling that someone else is touching my body" (touched-by-other; F(1,36) = 14.195, p = .001). However, the latter feeling was rated stronger in the asynchronous (M = 4.52, SD = 1.42) than the synchronous condition (M = 2.57, SD = 1.74). As predicted, the reported intensity of the "feeling of a presence of another person behind" (FoP) was also significantly larger in the asynchronous (M = 3.89, SD = 1.79) than the synchronous (M = 2.26, SD = 1.79) condition (F(1,36) = 7.884, p = .008). The average ratings of both FoP items in the asynchronous condition were significantly higher than the ratings of the control items (all p < .01). The average ratings of the other four questionnaire items were all low (less than 3.15) and did not significantly differ across conditions (all p > .05).

Occurrence of the FoP. During the illusion condition (i.e. asynchronous sensorimotor stimulation) the questions related to the illusory presence (average touched-by-other and FoP) were rated higher or equal to 4 (on a 7-point Likert scale ranging from 0 to 6) by 74% of the participants ($p < 0.01$; two-tailed Fisher's exact test). We note that these percentages are comparable with those of previously reported but different illusory own body perceptions (e.g. the visuo-tactile rubber hand illusion by Ehrsson and colleagues [S10]; the tactile rubber hand illusion by Ehrsson and colleagues [5]). Moreover, 84% of the participants (i.e. 16 out of a total of 19 participants) reported significantly larger ratings in the asynchronous than in the synchronous condition ($p < 0.01$; two-tailed Fisher's exact test) in at least one of the two items used to subjectively assess the illusion. More specifically, 74% reported larger rating in the asynchronous condition for the touched-by-other question ($p < 0.01$); and 74% reported larger rating in the asynchronous for the somebody-behind question (FoP) ($p < 0.01$). Collectively, this shows that a significant majority of our participants experienced the illusion (as assessed through classical methods) and that this systematically occurred in the asynchronous, rather than the synchronous condition.

Self-location. As expected, participants drift significantly more backwards during the asynchronous than the synchronous condition ($F(1, 55.267) = 4.409$, $p = .040$). This posterior drift was thus found in the condition in which our subjects reported higher ratings of FoP and that somebody was touching their body.

Study 4 (healthy subjects)

Study 4 aimed at testing implicitly rather than explicitly (i.e. questionnaire) the presence of another person in the space close to the participants. Thus, we asked participants to estimate the number of people that they felt to be present close to them in the testing room ("how many people do you feel close to you?”), while they were using the sensorimotor robot in the synchronous and in the asynchronous conditions. Before starting the experiment, the subjects had seen and heard four people discussing and standing in the testing room, and were told that during the experiment some of these people could have been in the room close to them or not. During the experiment, no other person except the two experimenters and the participant were actually in the room, and nobody was ever close to the participant. In line with our prediction, data from study 4 show that in the experimental condition that is associated with the FoP (asynchronous condition) participants judged a significantly higher number of people being close to them ($M = 2.0$, $SD = 0.54$) as compared to the synchronous condition ($M = 1.6$, $SD = 0.71$, $F(1, 250.04) = 11.782$, $p < 0.01$; Figure 3C) .

FoP and other illusory own body perceptions

The FoP has often been mistaken for other illusory own body perceptions, such as out-of-body experiences, heautoscopy, or autoscopic hallucinations. The present findings highlight that the FoP is characterized by its own distinct phenomenology and fronto-parietal lesion location. The former conditions have been linked to a single and hemisphere-specific lesion site [18, 20] and to disorders of multisensory integration that do not involve the *sensorimotor* system. For instance, OBEs are attributed to *visuo-somatosensory-vestibular* disintegration [20, 29], heautoscopy to *visuo-somatosensory-interoceptive* disintegration, and autoscopic hallucinations to *visuo-somatosensory* disintegration [18, 30]. Instead, the present FoP data give most importance to abnormal integration of *sensorimotor* signals caused by focal lesion in the fronto-parietal cortex of either hemisphere. Comparing OBE and FoP, they are both illusory own body perceptions, but in the FoP the abnormal own body representation is assigned to another, whereas in an OBE it is assigned to self. We can only speculate, but differences in underlying abnormal integration of multisensory and sensorimotor signals and differences in brain lesion may account for such distinct self-identification patterns. We argue that the vestibular abnormalities leading to changes in the location of the first-person perspective lead to self-identification with the abnormal own body representation in the case of OBEs, whereas abnormal sensorimotor signals during the FoP are not sufficient to induce self-identification with the abnormal own body representation that is hence experienced as another.

FoP in mountaineers

We can only speculate about the FoP in mountaineers. Extreme mountaineering is associated with visual deprivation and prolonged exposure to low oxygen level in extreme altitudes (above 6000 meters) and when climbing without artificial oxygen. If such conditions are combined with rapid ascends or descends and abnormal sensorimotor signals from one's body (due to bodily exhaustion, extreme fatigue, and repetitive gait), the occurrence of the FoP and other illusions and hallucinations may be facilitated [3, 4, 11, 12]. Such physiological conditions could impact the integration of sensorimotor signals in the described cortical network, further boosted by anxiety and solitude, and facilitate illusory and hallucinatory states during mountaineering, including the FoP [3].

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3.6 SENSORIMOTOR MANIPULATION OF THOUGHT AGENCY AND THOUGHT INSERTION IN HEALTHY SUBJECTS

SENSORIMOTOR MANIPULATION OF THOUGHT AGENCY AND THOUGHT INSERTION IN HEALTHY SUBJECTS

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ABSTRACT

The sense of agency emerges from experienced congruence between own actions and their sensory consequences and is believed to depend on internal forward models, which predict the sensory consequences of self-generated action. Increasing evidence suggests the existence of abnormal predicting mechanisms in schizophrenia, linking the abnormalities in action monitoring to the positive symptoms, such as thought insertion. However, despite that predictive coding view offers a parsimonious theoretical account to explain the link between deficits in action monitoring and formation of delusional beliefs, a sufficient experimental data is still missing to support the view. In the present paper we investigated how a robotically induced sensorimotor incongruence affects not only the sense of agency for self-produced tactile stimuli but also the sense of agency for own thought processes in healthy subjects. In a series of three studies, healthy participants manipulated the master robot device in front of them while the slave robot applied the tactile stimuli to their back either in synchrony with their movements or delayed by 500 ms. While manipulating the robot, the participants performed a verbal source-memory task (Study 1), verbal fluency task (Study 2) or word numerosity judgment task (Study 3). We show that robotically induced sensorimotor mismatch (asynchronous condition) lead to schizophrenia-like symptoms, such as increased source memory misattribution and subjective sense of reduced thought agency (Study 1), as well as increased subjective (Study 2) and behavioural indices of thought insertion (Study 3). The current results are interpreted within the framework of predictive coding view and provide experimental evidence for the link between aberrant predictive signalling mechanisms, impairments in action-monitoring and delusional experiences of thought insertion.

Key words: sensorimotor integration, agency, thought insertion, schizophrenia, prediction

1. INTRODUCTION

Self-consciousness is one of the most complex and alluring human features, and although it has been in the focus of multiple disciplines, its origin, mechanisms, and functions are still not well understood. Better understanding of what self-consciousness is can be achieved by understanding the disorders where the sense of self breaks down. One of the most severe and devastating self-disorders is schizophrenia, clinically manifested in hallucinations, delusions and disorganized thought processes (American Psychiatric Association, 2000, *DSM-IV*).

A central aspect of schizophrenia is the loss of boundaries between the self and external world, reflected in the loss of the sense of agency, i.e. ability to recognize and attribute a motor action, thought, or emotion to its proper agent (Blakemore, Wolpert, & Frith, 2002; Fletcher & Frith, 2009; Jeannerod, 2003). The loss of the sense of agency in schizophrenia is most obvious in the first-rank symptoms, according to Schneider classification, characterized by auditory verbal hallucinations (AVH), delusions of control, thought withdrawal, and perhaps the most striking, thought insertion (Schneider, 1959). In the latter, the patient experiences to have thoughts made by an outside force or agent and inserted into his mind. Thus, the patient experiences these thoughts as occurring within the boundaries of his own mind, but he does not attribute the source of the thoughts to himself (Bortolotti & Broome, 2008; Campbell, 1999; Mullins & Spence, 2003; Stephens & Graham, 1994)

A prominent theory about the mechanisms of positive symptoms in schizophrenia argues that certain symptoms in schizophrenia are due to deficits in self-monitoring, i.e. in the ability to distinguish the self-generated actions or thoughts from those that have been externally generated (Feinberg, 1978; Frith, Blakemore, & Wolpert, 2000; Frith & Done, 1988; Frith, 1992). The theory is based on the internal forward model of sensorimotor integration, which claims that a motor command is accompanied by an efference copy (von Holst, 1951) to make a prediction about the sensory consequence of the action (Helmholtz, 1866; Sperry, 1950). The prediction is compared with the actual sensory consequence in order to monitor and correct the motor commands (Wolpert & Ghahramani, 1995). Self-produced sensations are attenuated when the prediction and actual sensory feedback signal match (Shergill et al., 2013). Conversely, if the sensory signal does not match the prediction or if it occurs without the preceded prediction, as it normally happens for externally generated sensory signals, no sensory attenuation occurs and the signal is interpreted as externally generated. This mechanism of self-monitoring based on the comparator model thus enables the discrimination between self- and externally produced motor actions and sensory stimuli and is at the basis of the sense of agency (Jeannerod, 2003). Several studies demonstrated that patients with schizophrenia have deficits in sensory attenuation of self-generated motor actions (Blakemore et al., 2002; Ford, Roach, Faustman, & Mathalon, 2008; Shergill et al., 2014; Shergill, Samson, Bays, Frith, & Wolpert, 2005; Teufel, Kingdon, Ingram, Wolpert, & Fletcher, 2010) and agency attributions (Daprati et al., 1997; Franck et al., 2001).

Under this general framework, the comparator model has also been influential in explaining auditory verbal hallucinations (AVH), one of the cardinal symptoms of schizophrenia. When the deficit in the comparator model of a schizophrenic patient occurs for his inner speech, internal voices are not attenuated and therefore perceived by the patient as originating from an external agent. A large body of clinical and experimental data supports this explanation, showing that AVH can also be explained by deficits in action self-monitoring. For example, schizophrenia patients showed to have increased subvocal activity during AVH (David, 1994; Gould, 1949; Green & Kinsbourne, 1990; Inouye & Shimizu, 1970; Junginger & Rauscher, 1987). Furthermore, whereas neurophysiological and neuroimaging data of healthy subjects show suppression of cortical activity during self-generated overt speech (Creutzfeldt, Ojemann, & Lettich, 1989; Ford et al., 2001; Fu et al., 2006; McGuire, Silbersweig, & Frith, 1996; Müller-Preuss & Ploog, 1981), schizophrenia patients, as compared to healthy controls, show reduced suppression of such cortical response (Ford & Mathalon, 2004, 2005; Ford et al., 2001; Ford, Roach, Faustman, & Mathalon, 2007; Heinks-Maldonado et al., 2007).

An impaired comparator mechanism has also been proposed to underlie thought insertion (Feinberg, 1978; Frith & Done, 1988; Frith, 1992). In line with this proposition, thoughts need to be considered as an analogue of motor actions or as an inner speech (Feinberg, 1978; Hughlings Jackson, 1958; Watson, 1930). However, the comparator model theory fails to provide sufficient evidence for the assumptions that thoughts are in fact motor commands, and that efference copy, suppression, and sensory consequence exist for the thought processes (Campbell, 1999; Spence, 2001; Vosgerau & Newen, 2007). In addition, the theory does not establish a link between the defective prediction mechanism resulting in perceptual anomaly and the formation of delusions. For example, how does the loss of sense of agency for one's own motor actions or thoughts lead to the delusions of control and misattribution of own mental content to an external force or agent?

Recently, the positive symptoms of schizophrenia, including AVH, delusions of control and thought insertion have been explained in the view of hierarchic predictive coding framework (Apps & Tsakiris, 2014; Clark, 2013; Fletcher & Frith, 2009; Friston, Kilner, & Harrison, 2006). This theoretical framework explains the formation of delusional beliefs and abnormal sense of thought agency by generalizing the internal forward models from action to thought processes. According to this account, we construct a model about the world in a probabilistic fashion, where the sensory signals are compared with prior predictions (beliefs) about the sensory event, and in case of mismatch, prediction errors are fed back in a hierarchical manner to update the predictions. In this view, inferences about the sensory event and the actual sensory signals are not properly integrated in the case of schizophrenia, resulting in altered error prediction mechanisms. Inadequate prediction errors consequently fail to fully update the predictions, which in turn strengthen the perceptual anomalies. This self-enforcing cycle of aberrant bottom-up sensory and top-down cognitive interaction may therefore underlie the formation of delusional beliefs. Although the predictive coding theories may provide a parsimonious and unifying theoretical perspective of the emergence of positive symptoms, a large body of experimental data is yet needed to support this view.

In a recent study we showed that experimental perturbations of sensorimotor integration through a robotic system reduced the sense of agency for self-produced tactile sensations and induced misattribution of own sensorimotor representation to an external agent. In this study participants performed stroking hand movements with a master robot in front of them, while they received a delayed tactile feedback at their back through a slave robot. This manipulation of the spatio-temporal congruency between movements and sensory feedback induced in participants schizophrenia-like illusory sensations of being in the presence of another person, i.e. the feeling of a presence (Blanke et al., 2014).

The aim of the present paper was to investigate whether such robotically induced sensorimotor mismatch influences not only the sense of agency for own movements but also for own thoughts in healthy subjects. We here report a series of behavioural studies carried out on the same robotic platform. In Study 1 we showed that altered sensorimotor integration impairs the ability to discriminate between self- and externally-produced words in a source monitoring task and reduces accompanying sense of agency for the self-generated words as measured through subjective reports. In Study 2 we showed that the robotically induced sensorimotor conflict also results in subjective reports of thought insertion. These reports were further followed up with a behavioural measure of thought insertion in Study 3, where participants made numerosity judgments about the quantity of words they produced in a word fluency task while operating the robotic system. We showed that the judgments were elevated when they operated the robotic system in the asynchronous mode, i.e. in the condition that induced sensorimotor mismatch.

The present findings are the first to demonstrate that experimentally induced incongruence between sensory predictions for own motor actions and actual sensory feedback reduces the sense of agency for own thoughts and induces thought insertion in healthy subjects. As such it provides the first experimental evidence for the link between altered sensorimotor predictions and illusions of thought insertion in healthy people.

2. METHODS

Participants

In total, 73 subjects participated in three studies. All participants were recruited by an advertisement at the EPFL campus (École Polytechnique Fédérale de Lausanne, Switzerland). They were native French speakers, had normal touch perception and no psychiatric or neurologic history as assessed by self-report. Each participant only took part in one experiment. All participants were naive to the purpose of the study and gave written informed consent to take part in the study. The study was approved by the EPFL ethics committee (Comité d'éthique de la recherche humaine) and was conducted according to the ethical standards laid down in the Declaration of Helsinki. Participants gave written informed consent after they were explained the study procedures and were reimbursed for their participation with 20 CHF.

Robotic sensorimotor system

To experimentally create sensorimotor mismatch we adapted a bilateral master-slave robotic system that has been recently used to manipulate changes in bodily self-consciousness (Blanke et al., 2014; Hara et al., 2011, 2015). This system is composed of a master haptic interface, the Phantom Omni (SensAble Technologies), and a three degree-of-freedom (DOF) slave robot. The slave device consists of a belt-drive mechanism and a parallel-link mechanism. The belt-drive mechanism is made up of a belt linked to a direct-drive DC motor (RE 40, Maxon) moving a carrier on a linear guide allowing movements in the y (forward-backward) direction. The parallel-link mechanism is actuated through two harmonic drive motors (RH-8D 6006, Harmonic Drive Systems) and enables both tapping and stroking in x (right-left) and z (up-down) directions. The overall workspace of the slave device is 200mm in the x direction, 250mm in the y direction, and 200mm in the z direction. The system was controlled through an application programmed in Visual C++ (Microsoft) at a sampling rate of 1 kHz. The latency related to information transfer delays and computational processing necessary for mapping the master device movements to the slave device movements (i.e. touching the back of the participants) was equal to 1ms. The system had a bandwidth of approximately 2.5 Hz allowing a good synchrony between the master and the slave even during rapid and abrupt changes in velocity and direction (Hara et al., 2011). This allowed reducing the constraints on participants' movements. The robotic system is shown in Figure 1.

General procedure

In each study, the participants were first explained the task and informed about the general procedure of the experiment. Then they were instructed on how to use the robotic device to apply touch on their back through the tip of the slave device. The experimenter demonstrated the type of movements they were supposed to perform during the experimental blocks. In particular, they were asked to perform tapping movements in front of them by holding the master device with both hands, while receiving the touch on their back by the slave device. They were allowed to tap in different directions (up-down, left-right) resulting in different touches applied on their back within a workspace of 200x200mm. In the training session the participants used the system in the synchronous mode for about 1 minute without being blindfolded.

*** Insert here Figure 1***

3. STUDY 1: BEHAVIOURAL MEASURE OF THOUGHT AGENCY

In Study 1 we investigated whether altered sensorimotor integration induced through the robotic system by delaying the tactile feedback of performed movements reduces the sense of agency for own thoughts. In order to operationalize thought generation, we used a word association task, where participants had to produce a word associated to a provided cue word. Thus, each association corresponded to an internal thought. In order to obtain a behavioural measure of thought agency, we adapted a source-memory task (Slamecka & Graf, 1978). In this task participants had to judge whether heard words were previously generated by them. The performance on this task reflects the ability to source-monitor own mental processes and discriminate the self- from externally-generated information (Honey et al., 2006; Raye & Johnson, 2013). The sense of agency is necessary to enable the source-discrimination by delineating self-produced from externally produced words, and it was shown to improve the implicit and explicit memory for the events or generated words (Daprati, Nico, Franck, & Sirigu, 2003; Daprati, Nico, Saimpont, Franck, & Sirigu, 2005; Franck et al., 2001; Kanemoto, Asai, Sugimori, & Tanno, 2013). We therefore hypothesized that operating the robotic system in the asynchronous mode would blurr the boundaries between self and other and result in impaired performance on the source-memory task and reduced subjective sense of agency for the generated word associations.

3.1 METHODS

Participants

35 (11 females) subjects participated in Study 1. Their age ranged between 18 and 30 years (M = 20.5, SD = 2.5). One participant was left-handed. Due to a technical problem with the robotic system, two participants were not able to finish the experiment, and their data was therefore excluded from the analyses.

Behavioural paradigm: Self-generation effect

In order to explore the effect of experimental manipulation on the sense of agency for thoughts, we adapted the Generation effect paradigm, a source-memory task first described by Slamecka and Graf (1978). In this paradigm, the participants are first presented with a list of words. For each presented word, they are asked to either read aloud an associated word (other-generated word) or to freely generate a word semantically associated to the cued word (self-generated word). At the end of the encoding phase, they are presented with another list of words, and for each word they are asked to indicate whether they had read or generated it before. Typically, the self-generated items are remembered better than the externally presented items. This phenomenon, termed generation effect, has been shown to be very robust, and it was found in recognition as well as recall tasks, and with a variety of materials, generation rules and retention intervals (Hirshman & Bjork, 1988).

In our study, the material used for the encoding of self-generated words (self-generation conditions) consisted of two alternative lists, each containing 35 cue words and 35 letter cues. Similarly, we used two alternative lists of 35 word pairs for the encoding of other-generated words (other-generation conditions). A detailed description of the stimuli selection and acquisition can be found in Supplementary material. All the words and letter cues were presented to participants as auditory stimuli during the experimental blocks, using MATLAB software (MathWorks, Inc.). In the self-generation conditions the participants heard 35 cue words, each followed by a cue letter. They were instructed to generate an associated word, which had to start with the specified letter, and utter it aloud. If the participant's generated word matched the predicted word (target word), the experimenter registered it, and the word was later used in the recognition task during the test phase. Therefore, all the prediction-matched words were played back to the participants with a matched number of distractor words. The order in which the cue words in the encoding phase and the prediction-matched and distractor words in the test phase were presented was randomized. In the test phase participant had to determine for each played word whether it is a word he or she generated or not. In the other-generation conditions, participants merely listened to 35 audio-played word pairs, and were instructed that they would be later tested for recognition of the second word in a pair. In the test phase all the second words in a pair were played back together with 35 distractor words in a randomized order. In the self-generation conditions the time interval between the cue word and cue letter presentation was 1s, and participant's performance was self-paced in the encoding as well as in the test phase. In the other-generation conditions, the time interval between the words in a pair was 1s and 2.5s between the consecutive pairs. The rate of stimuli presentation in the test phase was self-paced. The participant had to determine whether he or she heard the word before or not. Participants' performance was quantified by the d-prime score.

Questionnaire: Feeling of a presence

To demonstrate that the robotic setup induced sensorimotor mismatch and related self-other confusion, we administered the FoP illusion questionnaire, which was used in our previous study (Blanke et al., 2014). The questionnaire consists of 8 items, referring to the illusory experience of self-touch (i.e. the sensation that one is touching oneself: "I felt as if I was touching my body"), subjective displacement of one's self in front or behind one's own body ("I felt as if I was in front of my body" and "I felt as if I was behind my body"), and the feeling of a presence ("I felt as if someone else was touching my body" and "I felt as if someone was standing behind my body"). Other items served as control items for suggestibility (e.g. "I felt as if I had no body"). Participants were asked to designate on a 7-point Likert scale, how strong they felt the sensation described by each item (0 = *not*, 6 = *very strong*).

Questionnaire: Subjective loss of thought agency

In order to measure the sense of agency and ownership for the self-generated and externally generated word associations we developed a short 3-item questionnaire. The items were designed based on the well described psychiatric phenomena of disorders of thought possession (Mellor, 1970; Stephens & Graham, 1994). Thus they were referring to the loss of the sense of ownership for the self-generated or heard associations ("It seemed as if the words I generated/heard were not my own", *thought ownership*), delusion of thought insertion ("It seemed as if the words I generated/heard were inserted into my mind", *thought insertion*) and loss of the sense of agency ("It seemed as if I was not the one who generated/heard the words", *thought agency loss*). Participants were asked to rate how strong they agreed with each described item on a 7-point Likert scale (0 = not at all, 3 = not certain, 6 = very strong).

Experimental design and procedure

In a 2 x 2 factorial repeated measures design we manipulated the *synchrony* between participant's movements and received tactile feedback (synchronous, asynchronous) and *generation source* (self, other). Each participant therefore completed 4 experimental conditions in a randomized order. In the synchronous conditions the executions of the slave device applying the tactile feedback were synchronized with the participant's movements, while in the asynchronous conditions the tactile feedback was delayed for 500ms.

During the experimental blocks, the participants wore headphones and were blindfolded. They were manipulating the robotic device when after 60s the encoding phase of the Generation task begun. In this phase, depending on the condition, they listened to either pairs of words (other-generation) or they generated their own words after hearing a cue word and a cue letter (self-generation) while still operating the robotic device. After the encoding phase, the participants stopped operating the robot and removed the blind folder to commence the test phase with the recognition task. At the end, they were administered the FoP and Thought agency questionnaires.

Data analyses

In order to avoid the ceiling effect in the recognition task of the self-generated words, only the data of the subjects who generated more than 50 % of expected associations (at least 18 words) were included into analysis. Also, the subjects who performed under the chance level in the recognition of other-generated words were excluded from the analysis, leaving the data of 22 participants for further analyses. D-prime scores for word recognition were analysed with a repeated measures ANOVA, using generation *source* (self, other) and *synchrony* (synchronous, asynchronous feedback) as two by two within-subject factors and *FoP score* as a covariate. Based on the recent finding that the FoP can be experimentally induced in healthy subjects due to a specific spatial and temporal sensorimotor mismatch (Blanke et al., 2014) we calculated the FoP score by subtracting the ratings of the FoP questionnaire item in the synchronous from the ratings in the asynchronous condition. Thus, higher FoP score indicated stronger FoP illusion due to the robotically induced sensorimotor mismatch. The ratings of the FoP illusion and Thought agency questionnaires were analysed with Wilcoxon signed-rank test (one-tailed, based on strong predictions about the direction of the effects from previous reports (Blanke et al., 2014)).

3.2 RESULTS

Behavioural paradigm: Self-generation effect

The analyses of the memory task performance replicate the classical self-generation effect (Slamecka & Graf, 1978), as the main effect of *source* was significant (self: M = 4.12, SD = 0.45; other: M = 2.28, SD = 0.65; F(1,20) = 180.86, p < .0001). Importantly, this self-effect was significantly modulated by the manipulation of the sensorimotor synchrony in relation to the experience of FoP (interaction between *generation source, synchrony* and covariate *FoP score:* (F(1,20) = 6.904, p = .016). To investigate this interaction, we split the sample into two groups according to the experience of FoP (No-FoP group: Fop score ≤ 0; FoP group: FoP score > 0) and tested whether the two groups differed in the modulation of the self-effect due to sensorimotor mismatch. Indeed, the mixed ANOVA on the strength of the self effect (calculated as d' self – d' other) showed a significant interaction between *synchrony* and *group (*F(1,20) = 7.217, p = .014). Post-hoc comparisons further showed a significant decrease of the self-effect in the asynchronous condition, but only in the group, which experienced the FoP (synchronous: M = 2.33, SD = 0.75; asynchronous: M = 1.53, SD = 0.83; one-tailed t-test: t(10) = 2.148, p = .029; No-FoP group: synchronous: M = 1.43; SD = 0.90; asynchronous: M = 2.07, SD = 1.04, one-tailed t-test: t(10) = 1.660, p = .064).

Questionnaire: Feeling of a presence

Participants experienced stronger sensation to be touched by other in the asynchronous condition (synchronous: M = 3.20, SD = 1.71; asynchronous: M = 3.84, SD = 1.78; one-tailed Wilcoxon signed-rank test: Z = -2.399, p = .008) and also reported stronger feeling of the presence in the same, asynchronous condition (synchronous: M = 2.80, SD = 1.48; asynchronous: M = 3.24, SD = 1.55; one-tailed Wilcoxon signed-rank test: Z = -2.361, p = .009). Conversely, the participants reported stronger illusory self-touch when they operated the robotic system in the synchronous mode (synchronous: M = 3.18, SD = 1.50; asynchronous: M = 2.24, SD = 1.43; one-tailed Wilcoxon signed-rank test: Z = -2.985, p = .002). The ratings of the control items were low and not significantly affected by the modulation of synchrony (M < 1.5, SD < 1.80, all p < .05), except the item: "I felt as if I was behind my body" (synchronous: M = 2.30, SD = 1.77; asynchronous: M = 1.82, SD = 1.47; one-tailed Wilcoxon signed-rank test: Z = -2.623, p = .005).

Questionnaire: Subjective loss of thought agency

The effect of synchrony modulation was observed for the sense of agency over self-generated thoughts. The participants reported reduced sense of agency ("It seemed as if I was not the one who generated the words") for the words they generated in the asynchronous (M = 2.21, SD = 1.728) as compared to synchronous condition (M = 1.73, SD = 1.625; one-tailed Wilcoxon signed-rank test: Z = -1.894, p = .029). The synchrony did not modulate the experience of thought insertion (synchronous: M = 2.97, SD = 1.610, asynchronous: M = 3.03, SD = 1.794; Z = - .340, p = .367) or ownership for self-generated words (synchronous: M = 1.55, SD = 1.348, asynchronous: M = 1.67, SD = 1.407; Z = - 0.537, p = .296), although in both cases ratings were higher in the asynchronous condition.

*** Insert here Figure 2 ***

3.3 DISCUSSION

In Study 1 we first replicated or previous findings (Blanke et al., 2014) showing that robotically induced delay between own motor movements and received tactile feedback at the back (asynchronous sensorimotor condition) induces the illusion of a presence of another person. Second, we also replicated the classical self-generation effect in the source memory task, proving that word associations are recalled better when they are self-generated as compared to when they are passively heard (Begg, Snider, Foley, & Goddard, 1989; Hirshman & Bjork, 1988; Slamecka & Graf, 1978). Importantly, we showed that the memory facilitating self-effect was reduced in the asynchronous sensorimotor condition, but only for those participants who experienced to be in the presence of an external agent. Furthermore, the sensorimotor mismatch also reduced the subjective sense of agency for self-generated word associations.

In the present memory task, we investigated whether a low-level sensory motor conflict, inducing experience changes, such as the feeling of being in a presence of another person, affects how well participants recognize the source of generated words. To this aim, we used the self-reference effect (i.e., difference in recognizing self vs. other generated words), which has been well evidenced in numerous studies in the memory domain (Rogers, Kuiper, & Kirker, 1977; Symons & Johnson, 1997) and we applied it to the field of sensorimotor conflicts and bodily illusions. We found that robot-induced sensorimotor mismatch suppressed the advantages of self-effect in the source-memory. Thus, the robot-induced mismatch between the participant's movements and tactile feedback perturbed the sensorimotor integration and error prediction mechanism so that the source of tactile feedback was misattributed to an external agent. Such misattribution of sensorimotor signals, reflected in an illusory belief that another agent is present nearby, further blurred the self-other distinction and was associated with reduced sense of agency for generated word associations, which were like-wise misattributed to an external source.

The results of the current experimental manipulation also relate to findings in schizophrenia, which is marked by impaired sense of agency. It was shown that schizophrenia patients demonstrated weaker self-effect advantage for source-memory, and were more prone to externally misattribute the source of the stimuli than healthy subjects (Daprati et al., 2005; Kanemoto et al., 2013). Experimentally induced sensorimotor mismatch in healthy subjects thus temporally altered the integration of sensory and motor signals and resulted in impaired ability of self-other discrimination, similar to performance observed in schizophrenia patients.

4. STUDY 2: SUBJECTIVE SENSE OF THOUGHT INSERTION

Impaired sense of agency for own thought processes, or thought possession disorder, is the hallmark of several positive symptoms in schizophrenia. The most common, and perhaps the most striking of them, is the delusion of thought insertion, where the patient experiences to have thoughts, which are generated by an outside force or agent and inserted into his mind (Bortolotti & Broome, 2008; Campbell, 1999; Mullins & Spence, 2003; Stephens & Graham, 1994). It has been proposed that such delusions arise due to deficient sensorimotor predictive mechanisms (Corlett, Taylor, Wang, Fletcher, & Krystal, 2010; Fletcher & Frith, 2009; Frith & Done, 1988, 1989).

Here we further investigated, based on the findings from Study 1, whether robot-induced loss of agency affects the subjective experience of thought possession disorders in healthy subjects, including thought insertion and related thought passivity phenomena. For this reason the participants were asked to perform a phonetic verbal fluency task in order to engage them in a controlled thought generation process, while operating the robotic platform in asynchronous or synchronous mode, so to induce or not the FoP. Their subjective experiences of thought possession disturbances were then assessed through ratings of a detailed questionnaire.

4.1 METHODS

Participants

19 (9 females) subjects participated in Study 2. Their age ranged between 18 and 28 years (M =20.3, SD = 2.4). Two participants were left-handed. One participant was excluded from the data analysis due to misunderstanding of the experimental procedure.

Questionnaire: Thought insertion

In order to systematically investigate the effect of robot-induced sensorimotor mismatch on the changes in the subjective sense of thought agency and ownership, we designed a detailed, 12-item questionnaire. The items were constructed based on the literature on thought possession disorders (Konings, Bak, Hanssen, van Os, & Krabbendam, 2006; Mullins & Spence, 2003; Raine, 1991; Schultze-Lutter, Addington, Ruhrmann, & Klosterkötter, 2011) and referred to the phenomenology of *thought insertion* (ex. "It seemed as if some outside force or person has put certain thoughts in my mind"), *thought influence* (ex. "It seemed as if some outside force or person has influenced some of my thoughts"), *thought ownership* (ex. *"It seemed as if certain thoughts I had belonged to someone else"*) and *thought withdrawal* (*ex. "It seems as if some of my thoughts have been removed from my mind"*). Other items, which served as control for suggestibility, pertained to positive psychotic symptoms but not to disorders of thought possession, i.e. *parasite thoughts ("It seemed as if the train of my thoughts have been interrupted by some unimportant "parasite" thoughts"), thought echoing (*"It seemed as if some of my thoughts were echoed back to me")*,* and *voice distortion (*"It seemed as if my voice became distorted"). The participants were asked to rate how much they agreed with each questionnaire item on a 7-point Likert scale (0 = not at all, 3 = not certain, 6 = very strong).

Experimental design and procedure

As in Study 1, blindfolded participants operated the robotic sensorimotor system, while they simultaneously performed a phonetic fluency task. In a repeated measures design we only manipulated the *synchrony* between participant's movements and tactile feedback. Thus, participants manipulated the robotic system in synchronous and asynchronous mode for 3 minutes. At the beginning of each condition, they heard a French phoneme through headphones, and were then given three minutes to generate as many words starting with the specified phoneme as they could. At the end of each block they were asked to answer the thought insertion questionnaire while referring to their thinking process during the task. The order of synchronous and asynchronous conditions was counterbalanced across the subjects. To assess the intensity of the FoP illusion, participants were also asked to operate the robot for 60s in both, synchronous and asynchronous mode, being blindfolded and instructed to only focus on their motor movements and tactile feedback, after which they were given the FoP illusion questionnaire. The FoP assessment blocks were performed either before or after the experiment in order to counterbalance possible cognitive bias from responding to one questionnaire onto the other. The description of the auditory word stimuli and their acquisition is detailed in Supplemental material.

Data analyses

A non-parametric comparison of the item ratings between synchronous and asynchronous mode of stimulation was performed with two-tailed Wilcoxon signed rank test. In order to identify the items with maximal between-condition variation we compared the ratings in synchronous and asynchronous condition for each questionnaire item separately. The analysis of the relationship between the ratings of the Thought insertion questionnaire and the ratings of the FoP was performed with 2-tailed Pearson's bivariate correlation coefficient analysis.

4.2 RESULTS

Analyses of the questionnaire data revealed that the synchrony between participants' movements and received tactile feedback significantly modulated ratings of the questionnaire items related to thought insertion and thought influencing. In particular, as compared to synchronous, the asynchronous mode of stimulation resulted in significantly higher ratings of the item on *thought insertion*: *"It seemed as if someone else has been thinking certain thoughts in my mind"* (synchronous: M =1.61, SD = 1.38, asynchronous: M = 2.00, SD = 1.41; Z = 2.111, p = .035), item on *thought influencing*: *"It seemed as if the robot behind influenced some of my thoughts*" (synchronous: M = 1.89, SD = 1.49, asynchronous: M = 3.33, SD = 1.64; Z = 2.345, p = .019) and marginally significant higher ratings of the item of *thought insertion*: *"It seemed as if the robot put certain thoughts in my mind"* (synchronous: M = 1.67, SD = 1.33, asynchronous: M = 2.5, SD = 1.76; Z = 1.911, p = .056). The ratings of other questionnaire items were not significantly modulated by the sensorimotor mismatch (all p > .05). Detailed results are reported in the Supplemental material.

Interestingly, the asynchronous-synchronous difference in the ratings of the item *"It seemed as if the robot behind influenced some of my thoughts*" (r(18) = .662, p = .003) and of the item ratings *"It seemed as if the robot put certain thoughts in my mind"* (r(18) = .636, p = .005) significantly positively correlated with the strength of experienced FoP as induced by the robot (FoP score: asynchronous-synchronous difference).

*** Insert here Figure 3 ***

4.3 DISCUSSION

The results of Study 2 show that participants reported stronger subjective experiences of thought influencing during the asynchronous as compared to synchronous sensorimotor condition. Individual item analysis further showed that the robot-induced sensorimotor mismatch in particular increased the subjective misattribution of own thought processes to an external source, and resulted in stronger experience that the thoughts are influenced and/or inserted by the robot. The latter two ratings also highly and positively correlated with the strength of experienced FoP.

We here show that experimentally induced perturbation of the brain's sensorimotor integration mechanisms results in blurring of the boundaries between self and other, and induces an illusion that own thinking processes are controlled by an external source. Such delusional beliefs of thought control are otherwise a hallmark of schizophrenic pathology (Mellor, 1970). Thus, the transiently induced loss of thought agency through experimental alterations of sensorimotor integration in healthy subjects may share similar mechanisms that underlie the formation of delusional beliefs in schizophrenia.

Nevertheless, these results should be interpreted with caution as first, the questionnaire analysis was exploratory and no correction for multiple statistical tests was employed. In this view, the present findings should be regarded as a proof of concept and should serve as a guide to construct a more precise assessment tool in the future research. Second, one could argue that the increased ratings of thought influencing and thought insertion in the asynchronous condition (as compared to synchronous) might be interpreted as a response of subjects to a more disturbing nature of asynchronous condition. However, if this were the case, the asynchrony-dependent increase in ratings should also been observed for control items, which actually did not occur.

5. STUDY 3: BEHAVIORAL MEASURE OF THOUGHT INSERTION

In order to obtain an objective indicator of thought insertion we have designed a behavioural task, based on the person numerosity task (Blanke et al., 2014). In the latter a blindfolded and sound-masked subject has to make judgments about how many people are in the part of the room close to him while he is operating the robotic system and no person is actually present. As the study showed, participants made elevated numerosity judgments when they operated the robotic system in the asynchronous mode, i.e. when a delay was inserted between the performed movements and received tactile feedback (Blanke et al., 2014). In a similar manner we here investigated whether such robotically induced sensorimotor mismatch would also affect numerosity judgments of own thoughts. We conceptualized thoughts as words that participants either actively generated during a phonetic fluency task (self-generated) or passively listen to (other-generated) while operating the robotic system. The implicit sense of thought insertion was measured through judgments of how many words a participant generated or listened to. We predicted that during the asynchronous mode the numerosity judgments of the self-generated words would be elevated as compared to the judgments in the synchronous mode. To exclude that the difference is due to a higher attention load in asynchronous condition, no difference between synchronous and asynchronous conditions should be observed for the conditions when participants only listened to the words.

5.1 METHODS

Participants

19 subjects (6 females) participated in the second study. They were all right-handed and their age ranged between 18 and 23 years (M =20.9, SD = 2.0).

Behavioral paradigm: Thought numerosity judgments

We have adapted the phonetic fluency task that was used in Study 2. Participants were asked to estimate the number of words that they have either generated themselves or listened to while operating the robotic sensorimotor system. In a 2 x 2 factorial repeated measures design, we manipulated the *synchrony* between participant's movements and received tactile feedback (synchronous, asynchronous) and *generation source* (self, other). In the asynchronous conditions, the tactile feedback received at the back was delayed by 500ms. In the self-generation conditions, a starting phoneme was played to participants through headphones and they were instructed to generate as many words starting with the specified phoneme as they could in a given time period (phonetic fluency task), which randomly varied between 15 and 30s. The experimenter counted and registered the words, and immediately afterwards, the participant had to estimate how many words she or he had generated. In the other-generated conditions, the participant listened to a list of words, consisting of between 6 and 10 words. The number randomly varied throughout the trials. To prevent participants from counting the words, and to match the conditions for attention and cognitive load, they had to determine whether each word they heard contains a phoneme, specified at the beginning of a trial in the other-generated conditions. The words were played to participants with an inter-stimuli interval of 2.5s. All the words and phoneme cues were presented to participants as auditory stimuli using MATLAB software (MathWorks, Inc.). The description of the auditory word stimuli and their acquisition is detailed in Supplemental material.

Each condition was repeated three times, and each repetition consisted of 4 trials, resulting in total of 12 numerosity judgments per condition. The order of repetitions of different experimental conditions was randomized across the experiment and across the participants. The dependent variable was the rating difference, calculated by subtracting the actual number of played or produced words from the judged number. Prior to the beginning of the experimental session, participants went through a training session, comprising one repetition of each condition. To assess the intensity of the FoP illusion, participants were also asked to operate the robot for 60s in both, synchronous and asynchronous mode, being blindfolded and instructed to only focus on their motor movements and tactile feedback, after which they were given the FoP illusion questionnaire. The FoP assessment blocks were performed either before or after the experiment in order to counterbalance possible cognitive bias from responding to one questionnaire onto the other. The description of the auditory word stimuli and their acquisition is detailed in Supplemental material.

Data analyses

Two trials where two subjects failed to generate any word within the given time limit were discarded from the analyses. The differences between the numerosity judgment and actual number of words (judgment accuracy) were averaged within each condition for each participant and then analysed with repeated measures ANOVA where *generation source* and *synchrony* were used as within-subject factors.

5.2 RESULTS

Behavioral paradigm: Thought numerosity judgments

The statistical analyses of the numerosity judgment accuracy first revealed that the participants underestimated the number of words when they were generated by them (M = -0.90, SD = 1.13) as compared to those generated by the external agent (M = 0.55, SD = 1.11; main effect of *source*: F(1,18) = 23.306, $p < .0001$). Critically, this self-suppression depended on the mode of sensorimotor stimulation (*source* and *synchrony* interaction: F(1,18) = 7.274, p = .015). The post-hoc comparisons showed that the self-suppression effect was weaker (i.e. participants judged to generate more words) for the words generated during the asynchronous condition (M = -0.75, SD = 1.16) as compared to the synchronous condition (M = -1.05, SD = 1.17; two-tailed t-test: t(18) = 2.192, p = .042). Put in another way, the numerosity judgments for self-generated words in the asynchronous condition were more similar to the numerosity judgements for externally generated words. Importantly, this reduction in perceived numerosity could not be attributed to a generic cognitive effect due the pattern of stimulation, being more disturbing in either of the two conditions, because no difference between synchronous and asynchronous mode of sensorimotor stimulation was observed for the words generated by an external agent (synchronous: M = 0.69, SD = 1.20; asynchronous: M = 0.41, SD = 1.14; two-tailed t-test: t(18) = 1.668, p = .113).

To test the correlation between the numerosity judgment accuracy and experience of the feeling of the presence, we correlated the FoP score (asynchronous-synchronous difference) with the difference between synchronous and asynchronous conditions in the numerosity judgment of actively (self) generated words. The two measures positively and significantly correlated (r (18)= .477, p = .039). Thus, the stronger a participant experienced the FoP due to the sensorimotor mismatch, the weaker the self-suppression effect was in the asynchronous (as compared to the synchronous) condition.

*** Insert here Figure 4 ***

5.3 DISCUSSION

The results of study 3 revealed three key findings. First, the averaged word numerosity judgments were lower in the self-generation than in the other-generation conditions regardless of the sensorimotor stimulation mode. Second, this attenuation of the numerosity judgments for the self-generated words was reduced in the asynchronous sensorimotor stimulation condition, i.e. the condition inducing the FoP. Third, the strength of the FoP effect was positively correlated with the reduction of the self-suppression effect.

Suppressed response to self-generated stimuli has been well documented to occur on perceptual as well as on neural level and has been shown to generalize across several modalities, e.g. touch (Blakemore, Wolpert, & Frith, 1998; Shergill et al., 2013; Weiskrantz, Elliot, & Darlington, 1971), vision (Gentsch & Schütz-Bosbach, 2011; Hughes & Waszak, 2011), audition (Creutzfeldt et al., 1989; Ford et al., 2001; Fu et al., 2006; McGuire et al., 1996; Müller-Preuss & Ploog, 1981; van Elk, Salomon, Kannape, & Blanke, 2014; Weiss, Herwig, & Schütz-Bosbach, 2011), and even heart-beat processing (van Elk, Lenggenhager, Heydrich, & Blanke, 2014).

A mechanism of forward prediction signaling has been proposed to underlie self-suppression, enabling distinction between self- and externally generated stimuli and enhancing the perception of unpredictable sensory events. Our study extends these findings and suggests that the same principle of self-suppression previously reported for the motor and sensory modalities also applies to higher cognitive representations, such as the perceived quantity of mental content.

Importantly, we further show that the robot-induced sensorimotor mismatch lessened the self-suppression of numerosity judgments. Thus, in the asynchronous condition a mismatch between predictions about the tactile consequences of executed arm movements and actual sensory outcome led to misattribution of movement to an external source, so to induce the FoP. The present findings suggest that, at the same time, such sensorimotor mismatch propagated to the level of inner mental representations, blurring the distinction of mental content, attributed to one's self or to others. In this way, the numerosity judgments for self-generated words in asynchronous conditions resembled the numerosity judgments observed in the other-generation conditions. In other words, due to experimentally perturbed sensorimotor integration, participants perceived an elevated quantity of self-generated thoughts. Critically, the results from the correlation analysis showed that such numerosity increase (due to weaker self-suppression) positively correlated with the strength of the experienced illusion of being in the presence of another agent, induced by the robotic sensorimotor mismatch. These findings directly link the blurring of self-other representation at the sensorimotor level, the illusory presence of another person, and the self-other confusion in mental representations of thoughts.

The current results therefore provide a behavioral evidence for the link between altered sensorimotor predictions (Blakemore et al., 2002; Ford et al., 2008; Shergill et al., 2014, 2005; Teufel et al., 2010) and first rank symptoms such as thought insertion (Bortolotti & Broome, 2008; Campbell, 1999; Mullins & Spence, 2003; Stephens & Graham, 1994).

6. GENERAL DISCUSSION

The aim of this paper was to investigate whether experimentally induced sensorimotor mismatch affects the sense of agency for own thought processes in healthy subjects. To this goal we developed behavioural paradigms to measure the sense of thought agency – a subjective phenomenon – in an objective and quantifiable way. In a series of three studies, the participants were moving the master robot device in front of them while the slave robot applied the tactile stimuli to their back, matching the force, velocity and trajectories of the participant's movements. While operating the robot, the participants performed on a verbal source-memory task (Study 1), verbal fluency task (Study 2) or word numerosity judgment task (Study 3). The incongruence between expected sensory outcome and actual sensory feedback was created in the asynchronous conditions when the tactile feedback was delayed. Previous data showed that this condition was also associated with the feeling of being touched by someone else and of another person standing behind the participant (Blanke et al., 2014). Here we show that such robotically induced sensorimotor mismatch (as compared to synchronous sensorimotor conditions) and the concurrent feeling of a presence had an effect on cognitive processing, which resulted in increased source memory misattribution and subjective sense of reduced thought agency (Study 1), as well as increased subjective (Study 2) and behavioural indices of thought insertion (Study 3). The present studies also showed that the reduced sense of thought agency and its misattribution to an external agent positively correlated with the strength of the illusion to be in the presence of another person.

Comparator model, predictive coding and thought agency

The current results provide an experimental link between perturbed sensorimotor predictive mechanism and deficits in self-monitoring, leading to behavioural indices of reduced thought agency and thought insertion in healthy subjects. These findings are in line with previous account on the sense of agency for actions as arousing from the temporo-spatial correspondence between sensory predictions (of motor actions) and the actual sensory outcome. When such correspondence is disturbed, in this case by asynchronous stimulation, participants report loss of agency for their own action – i.e. they reported being touched by someone else. However, these present data also extend and go beyond the comparator model account for action agency, by showing that the same spatio-temporal conflict also influences agency for thoughts. Therefore not only the sensory feedback from one's own movement is attributed to an external agent, but also the self-generated thoughts are attributed to an external source.

We interpret our findings within the framework of the predictive coding account (Apps & Tsakiris, 2014; Clark, 2013; Fletcher & Frith, 2009; Friston et al., 2006). In line with this view, experimentally inserted temporal delay between motor actions and tactile feedback created a mismatch between sensory predictions (beliefs) based on prior learned experience (“If I move my arm I touch my body”) and the actual sensory outcome (incongruence between proprioceptive-motor signals and tactile feedback). This mismatch required an update of the prior belief regarding the sensorimotor event, leading to the most plausible interpretation that the subject is not the agent of the tactile stimulation (loss of agency). This prediction error propagated to higher order beliefs resulting in the agency misattribution to an external source, the illusion of a presence of another agent and impaired self-monitoring of own mental content. According to the predictive coding theory our model of the world is built through a constant reciprocal communication between the bottom-up sensory input and top-down influence of prior beliefs. Thus perception is always constructed based on prior expectations, and error signals from low-level predictions update higher-level predictions (Corlett et al., 2010). In this line of reasoning, the false belief about the source of the tactile event would further reinforce the perceived asynchronous sensorimotor stimulation as being “alien” and originating from an external entity, which would in turn influence the beliefs about the source of the mental content, resulting in reduced sense of thought agency. In this vein, it is tempting to speculate that the experimental sensorimotor mismatch first lead to loss of agency for one’s own action, which upscaled to the FoP illusion, which then reduced the sense of thought agency and increased the thought insertion indices in this order. However, our experimental design and the obtained data, at the moment, cannot inform about the causality and hierarchy of the relationship between the sensorimotor prediction error, FoP illusion, loss of thought agency and thought insertion.

Nevertheless, through the master-slave robotic system we were able to experimentally influence the sensory predictive mechanisms by creating temporal mismatch between participants’ motor movements and tactile feedback. This manipulation lead to impairment of self-monitoring, i.e. reduction and misattribution of the sense of agency for own body sensorimotor as well as mental representations in healthy subjects. These effects observed in healthy participants might resemble, in a minimal form, the delusional beliefs that characterize schizophrenia, as discussed in the next paragraph.

Predictive coding and schizophrenia

Altered predictive mechanism has been proposed to explain positive symptoms in schizophrenia. For example, deficits in sensorimotor predictions have been considered to underlie the emergence of AVH. In this view, the hallucinating patient fails to supress the sensory activation during inner speech due to impaired prediction error signalling. Signals related to inner speech are consequently perceived as more salient and unusual, leading to the belief formation that they were not generated by the patient himself (Fletcher & Frith, 2009; Ford & Mathalon, 2005; Frith, 1992).

Indeed, a large body of research shows evidence for altered predictive mechanism in schizophrenia. For example, impaired self-monitoring in schizophrenia has been repeatedly documented for perception of self-generated tactile stimuli (Blakemore, Frith, & Wolpert, 1999), in force-matching task (Shergill et al., 2005), in visuomotor tasks (Fourneret et al., 2002; Frith & Done, 1989; Malenka, Angel, Thiemann, Weitz, & Berger, 1986), overt (Cahill, Silbersweig, & Frith, 1996; Goldberg, Gold, Coppola, & Weinberger, 1997; Johns et al., 2001, 2010) and inner speech (McGuire et al., 1995). Several studies have also shown that the suppression of self-generated stimuli, which depends on prediction signalling mechanisms, was reduced in schizophrenia patients (Blakemore et al., 2002; Ford & Mathalon, 2005; Ford et al., 2001, 2008; Mathalon & Ford, 2008; Shergill et al., 2014, 2005; Simons et al., 2010; Teufel et al., 2010). Moreover, subjects with schizophrenia exhibited impaired source-memory for self-generated words (Brodeur, Pelletier, & Lepage, 2009; Moritz, Woodward, & Ruff, 2003; Vinogradov, Luks, Schulman, & Simpson, 2008).

Evidence for aberrant predictive signalling mechanism in schizophrenia has also been reported for passive perception. For example, it was shown that individuals with schizophrenia exhibit stronger top-down influence of prior false beliefs on visual perception, as it was shown they are less likely, compared to healthy individuals, to update incorrect interpretation of ambiguous visual material through its gradual disambiguation (Moritz & Woodward, 2006; Speechley, Whitman, & Woodward, 2010). Patients with schizophrenia also showed increased top-down effects of prior expectations on perception of facial expressions (Barbalat, Rouault, Bazargani, Shergill, & Blakemore, 2012; Cook, Barbalat, & Blakemore, 2012) and increased effect of imagery on perception of ambiguous auditory stimuli (Aleman, Böcker, Hijman, de Haan, & Kahn, 2003).

Although the exact underlying neural correlates of altered predictive coding in schizophrenia are still unknown, a large number of studies suggests that the failure to properly integrate error predictions and sensory evidence is due to altered brain connectivity (Corlett et al., 2010; Stephan, Baldeweg, & Friston, 2006; Stephan, Friston, & Frith, 2009). Diffusion tension imaging and structural network analyses studies have in majority identified decreased connectivity in the prefrontal cortex and between frontal, temporal, and parietal regions, and reduced interhemispheric connections (for reviews see: Canu, Agosta, & Filippi, 2015; Fornito, Zalesky, Pantelis, & Bullmore, 2012; Wheeler & Voineskos, 2014). Moreover, functional imaging of self-monitoring tasks showed that schizophrenia patients manifested impaired functional integration between the superior temporal and anterior cingulate cortex during self-other voice distinction task (Mechelli et al., 2007) and reduced connectivity between the medial prefrontal cortex and superior temporal gyrus during verbal source memory monitoring task (Wang, Metzak, & Woodward, 2011). Moreover, the connectivity of the default mode network, associated with self-referential processes and stimulus-independent thoughts (Gusnard & Raichle, 2001; Molnar-Szakacs & Uddin, 2013; Smallwood, Brown, Baird, & Schooler, 2012), was repeatedly shown to be abnormal in patients with schizophrenia (Bluhm et al., 2007; Broyd et al., 2009; Garrity et al., 2007; Orliac et al., 2013).

Thus, in essence, positive symptoms of schizophrenia may be regarded as a consequence of inadequate self-monitoring due to an aberrant prediction signalling mechanism stemming from altered brain connectivity. In our study, we manipulated the integration of motor signals with tactile feedback through insertion of a temporal bias. Thus, in asynchronous conditions we experimentally "disconnected" the prediction signals from the sensory feedback, and temporarily altered the brain's prediction signalling mechanism. Such specific sensorimotor stimulation resulted in a schizophrenia-like state, observed in objective and subjective misattribution of thought agency and indices of thought insertion in healthy subjects.

Limitations of the present study and outlook

Several possible limitations of the current study and future directions need to be addressed. First, the sense of agency for own movements and thoughts, as well as thought insertion, are subjective phenomena, which are traditionally studied through subjective reports and questionnaires. In order to gain an objective and quantifiable measure, we developed behavioural tasks, where words generated by participants were considered as "units" of thoughts and used as a proxy to quantify thought agency. Nevertheless, these thoughts were not spontaneously generated by participants, but were stimuli- and task-dependant. As such the cognitive process behind our behavioural task possibly differs from the thinking processes implicated in thought insertion (Mullins & Spence, 2003; Vosgerau & Newen, 2007). This should be taken into consideration when discussing the present results in terms of thought agency and induced thought insertion. Further research is also needed to support the findings presented in this paper. For example, confirming evidence would be to test whether a similar sensorimotor conflict with a feedback in another sensory modality would cause comparable delusional beliefs and as such point towards the existence of a general, modality-nonspecific, role of predictive mechanism in formation of delusions. Moreover, in order to support the parallels between our experimental manipulation and schizophrenia, the performance of the schizophrenia patients with positive symptoms on the same behavioral tasks outside the robotic platform should be comparable with the current results. Finally, the present behavioral study should be corroborated with neurophysiological and neuroimaging studies to elucidate the brain activation network associated with objective and subjective measures of thought insertion. For example, reduced neural connectivity should be observed during robotically induced sensorimotor mismatch in the asynchronous conditions and should be associated with behavioral indices of reduced thought agency in healthy subjects, and be comparable with neural abnormalities observed in individuals with schizophrenia.

In conclusion, in the present study we experimentally manipulated the brain's predictive mechanisms through a robotic interface. We created a temporal mismatch between participants' motor–proprioceptive signals and received tactile feedback. This manipulation not only resulted in misattribution of sensorimotor agency to an external agent but has also affected higher-level cognitive process of self-monitoring tested here in the source-memory and thought numerosity judgments tasks, leading to behavioural and subjective indices of reduced thought agency and experience of thought insertion in healthy subjects. The current findings provide a behavioural link between aberrant predictive signalling mechanisms, impairments in self-monitoring and delusional experiences of thought insertion, and as such corroborate the proposition that positive symptoms of schizophrenia arise due to an aberrant predictive coding mechanism. These findings can significantly advance the understanding of delusion formation and importantly contribute to early detection of schizophrenia.

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8. SUPPLEMENTAL MATERIAL

8.1 ACQUISITION AND PREPARATION OF AUDITORY WORD STIMULI

For Study 1 (Generation memory effect), 250 word association pairs were first selected from the database of word association norms containing a collection of French words (Alario and Ferrand, 1998). In order to balance the strength of association between the cue word and its associated target word across conditions we have recruited 10 native French speakers (2 females; 18 – 23 years, M = 20.1, SD = 1.66). They were given the selected 250 cue words and cue letters (first letter of the predefined target word) to generate associations. The strength of the association was defined as the ratio with which participants chose the target word. 70 association pairs with higher association strength (0.7 - 1) were then selected for the self-generated conditions to increase the probability of participant generating the target word. 70 association pairs with lower association strength (0.3 – 0.6) were used for the other-generated conditions. Another 140 words were selected from the database to be used as distractor words during recognition task. The association pairs were then sorted into 4 alternative word lists (2 for self-generated and 2 for other-generated conditions), each consisting of 35 word pairs, with balanced association strength. Similarly, the distractor words were divided into 4 lists, each containing 35 distractor words.

We verified, using the multivariate analysis of variance (MANOVA), that there is no significant difference in terms of frequency of use (www.lexique.org) and word length between the alternative lists (F(6, 544) = .494, p = .813) or between the target and distractor words (F(2, 271) = .001, p = .999).

The word set was then recorded by two male and two female native French speakers and registered in wav format with 11025 Hz sampling frequency. In all three studies, as well as during the pilot study (see below), the auditory word stimuli were played to participants in a gender-matched voice. In Study 1, two gender-matched voices were alternating between the encoding and testing phase in a balanced manner throughout the experiment.

8.2 PILOT STUDY: VERIFICATION OF THE GENERATION EFFECT WITH AUDITORY STIMULI

To confirm that the generation effect can be also achieved by using selected word stimuli presented in auditory modality we have, prior to the main study, conducted a pilot study without the robotic sensorimotor stimulation. 6 native French speaking participants (3 females, M = 20.6 years, SD = 2.7) were recruited to participate in this study. They completed two self-generated and two other-generated conditions in a randomized order. Two-tailed paired-sample t-test showed that the accuracy rate (t(5)=5.289, p = .003) as well as sensitivity (t(5) = 7,264, p = .001) in the recognition task was significantly higher for the self-generated words, demonstrating that the generation effect was replicated with the selected auditory word material.

8.3 THOUGHT INSERTION QUESTIONNAIRE

Questionnaire item	M		SEM		Z	p
	Sync	Async	Sync	Async		
Thought influencing						
It seemed as if the robot behind influenced some of my thoughts.	1.89	3.33	0.35	0.39	2.34	**.019**
It seemed as if some outside force or person has influenced some of my thoughts.	2.28	3.00	0.36	0.36	1.25	.213
Thought insertion						
It seemed as if someone else has been thinking certain thoughts in my mind.	1.61	2.00	0.32	0.33	2.11	**.035**
It seemed as if the robot put certain thoughts in my mind.	1.67	2.50	0.31	0.41	1.91	**.056**
It seemed as if some outside force or person has put certain thoughts into my mind.	2.44	2.44	0.34	0.42	0.36	.719
It seemed as if some thoughts (that were not my own) intruded my mind.	2.28	2.06	0.40	0.38	0.21	.831
Thought ownership						
It seemed as if certain thoughts I had belonged to someone else.	1.61	2.00	0.33	0.39	0.98	.325
Thought withdrawal						
It seemed as if some of my thoughts have been removed from my mind.	4.00	4.39	0.40	0.26	0.80	.422
Parasite thoughts						
It seemed as if the train of my thoughts have been interrupted by some unimportant “parasite” thoughts.	4.17	4.28	0.34	0.31	0.41	.685
Thought echoing						
It seemed as if some of my thoughts were echoed back to me.	2.72	2.89	0.52	0.40	0.05	.964

Voice distortion						
It seemed as if my voice became distorted.	2.33	2.61	0.59	0.54	0.88	.380
It seemed as if my speech became hard to understand.	3.22	2.94	0.55	0.56	0.94	.345

Table 1. Complete Thought insertion questionnaire, with average item ratings, standard errors of the mean for synchronous and asynchronous conditions, and Z and 2-tailed p-values of Wilcoxon signed rank tests for the differences between the ratings of synchronous and asynchronous conditions.

8.4 THE NUMBER OF GENERATED WORDS IN THE THOUGHT NUMEROSITY JUDGMENT

In Study 3 (Numerosity judgment) we used the same auditory verbal stimuli as in Study 1 (in total 420 French words and 22 phonemes). To verify that the found numerosity judgment differences were not due to the differences in the number of generated words between the experimental conditions we conducted repeated-measures ANOVA on the number of generated or heard words with *source* and *synchrony* as within-subject factors. The analysis showed that the number of generated words did not differ between the self-generation (M = 7.95, SD = 2.02) and other-generation conditions (M = 8.11, SD = 0.33; F(1,18) = 0.115, p = .738), neither it was modulated by the synchrony (synchronous: M = 8.18, SD = 1.18; asynchronous: M = 7.88, SD = 0.89; F(1,18) = 3.079, p = .096) or the interaction between the source and synchrony (F(1,18) = 0.944, p = .344).

8.5 ABSOLUTE ACCURACY IN THE THOUGHT NUMEROSITY JUDGMENT

To verify whether the variance in the numerosity judgments was not due to difference in cognitive load between the self- and other-generation conditions or between synchronous and asynchronous conditions, we analysed the variance of absolute accuracy. This was defined as a percentage of trials when the numerosity judgment was correct within each experimental condition. The repeated measures ANOVA showed that the absolute accuracy was not affected by the *source* (F(1,18) = 0.833, p =.374), *synchrony* (F(1,18) = 0.810, p = .380) or the interaction between them (F(1,18) = 1.118, p = .304).

8.6 REFERENCE

Alario, F. X. & Ferrand, L. 1998. Normes d'associations verbales pour 366 noms d'objets concrets. *L'année psychologique*, 659-709.

9. FIGURES AND LEGENDS

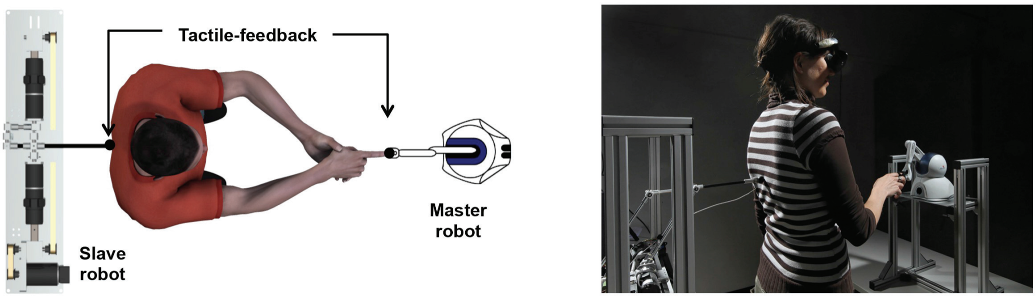

Figure 1. ***Robotic sensorimotor system.*** **LEFT:** Schematic depiction of the master-slave robotic system (Blanke et al., 2014). **RIGHT**: Participant is controlling the master device (Phantom Omni, SensAble Technologies) in front, while the slave part of the system copies the direction, force and velocity of participant's movements and applies tactile stimulation to the participant's back (RIGHT). In synchronous conditions the two devices move with perfect correspondence, in asynchronous conditions the slave device is delayed for 500 ms.

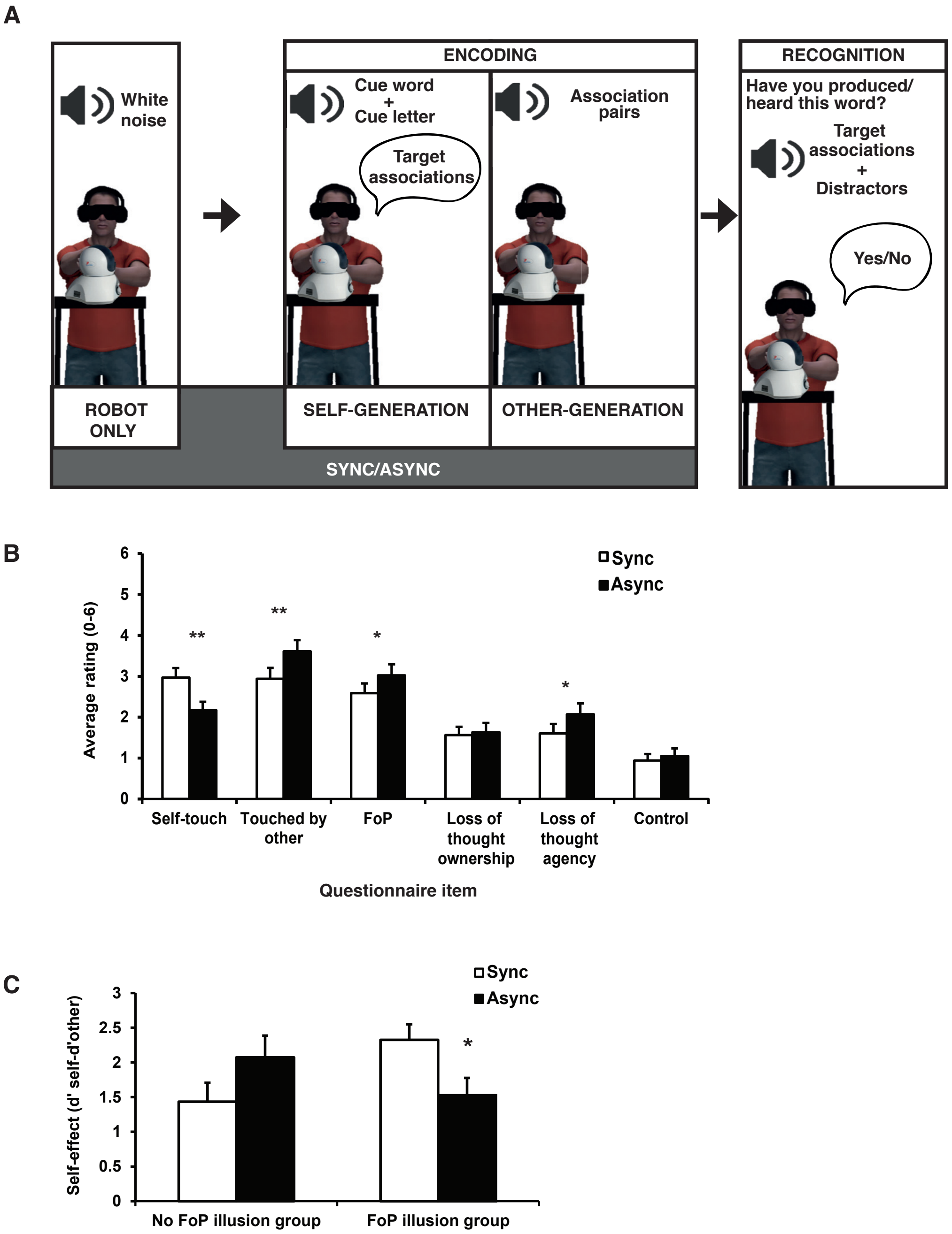

Figure 2. ***Study 1: Behavioral measure of thought agency (Experimental procedure and results).*** **(A)** Experimental procedure of the Study 3: Participant first operates the robotic system for 60s, while being blindfolded and sound isolated with white noise. Then the encoding phase starts where participant has to either generate word associations to heard cue words starting with the cue letter (self-generation condition) or he listens to pairs of associated words (other-generation condition). During the encoding phase participant operated the robotic system in synchronous or asynchronous mode. The encoding phase was followed by the memory recognition task, where participant listened to target associations he had generated and an equal number of distractors (self-generation condition) or association words he had heard and a matching number of distractor words (other-generation condition). For each word he had to answer whether he had generated (or heard) the word.

Participants did not operate the robotic system during the recognition task. **(B)** The graph shows average ratings of the FoP and Thought agency questionnaires for synchronous (Sync) and asynchronous (Async) condition. **(C)** The graph shows the average self-effect scores (d' self – d'other) in synchronous (Sync) and asynchronous (Async) conditions for the group without the feeling of a presence (no-FoP group) and group with the feeling of a presence (FoP group). The FoP group had significantly less self-advantage in the memory task in the asynchronous than synchronous condition. The error bars show standard error of the mean. * $p < .05$, ** $p < .01$.

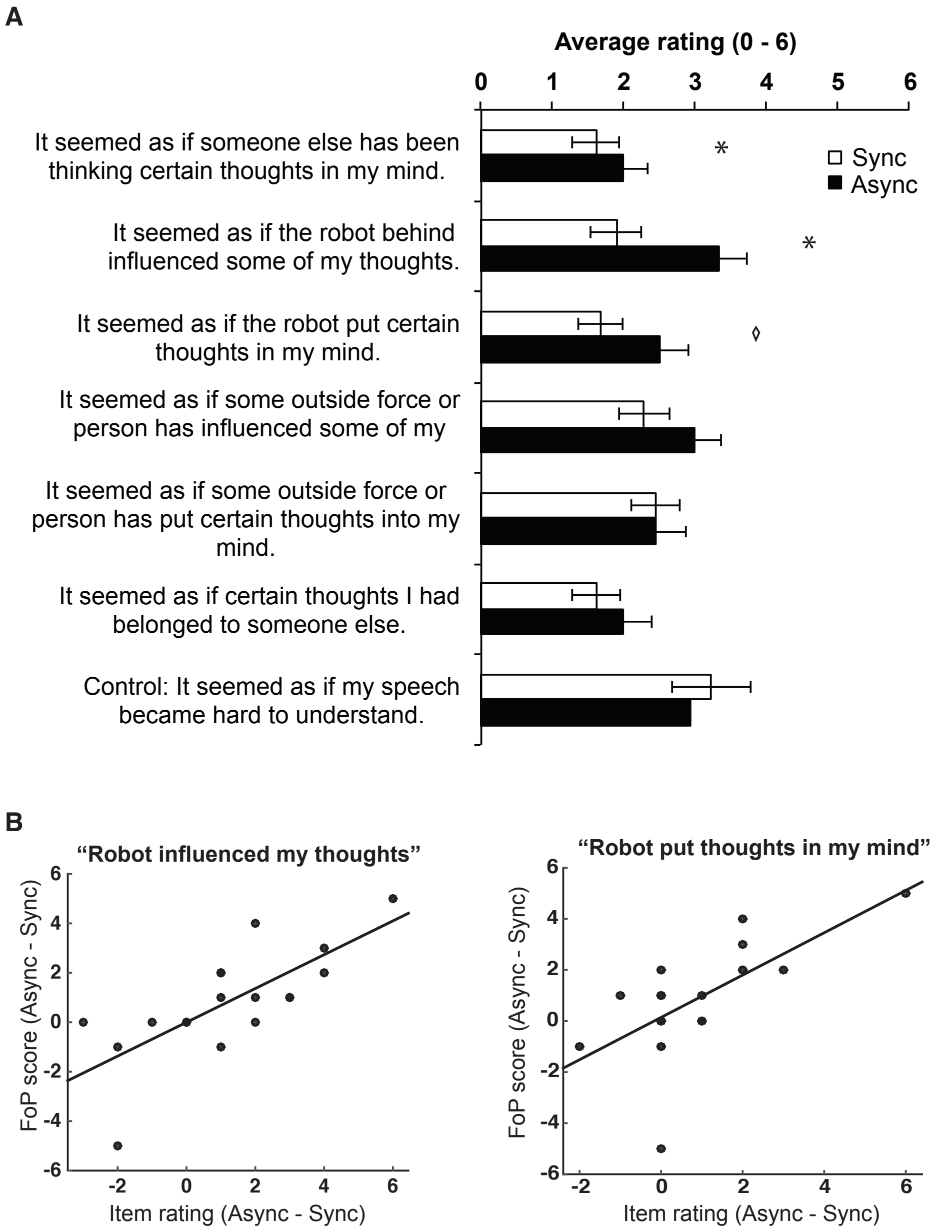

Figure 3. ***Study 2: Subjective measure of thought insertion (Results).*** **(A)** The graph shows the average ratings of Thought agency and thought insertion questionnaire for the synchronous (Sync) and asynchronous (Async) conditions. The error bars show standard errors of the mean. * $p < .05$, ** $p < .01$ **(B)** The scatter plots show significant positive correlation between the FoP score and ratings of thought influencing item (LEFT) and FoP score and thought insertion item (RIGHT).

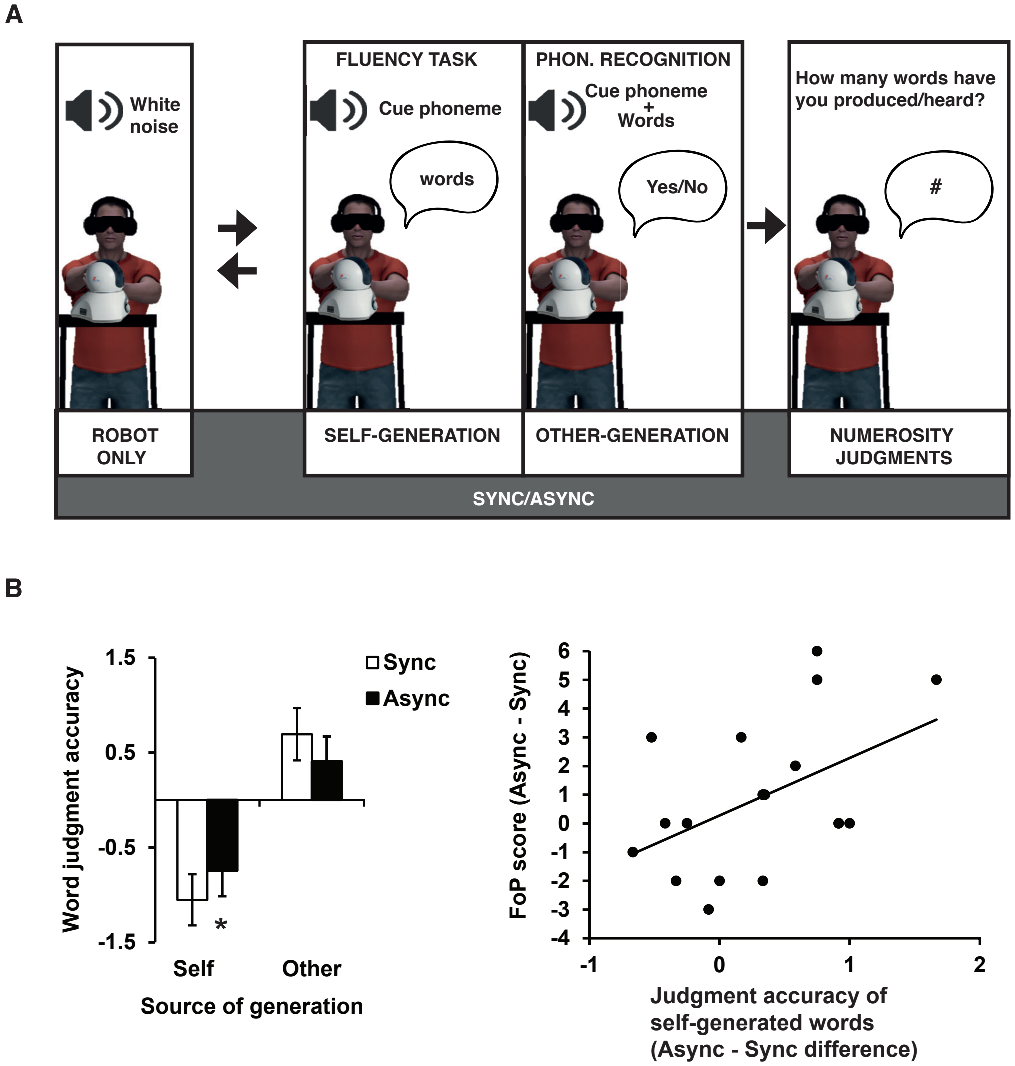

Figure 4. ***Study 3: Behavioral measure of thought insertion (Experimental procedure and results).*** **(A)** Schematic depiction of the experimental procedure in Study 3. Participant operated the robotic system in the synchronous (Sync) or asynchronous (Async) mode while they performed on the Thought numerosity task. In the self-generation conditions, a starting phoneme was played to participant and he was instructed to generate as many words starting with the specified phoneme as possible in a given time period, which randomly varied between 15 and 30s. Immediately afterwards, the participant had to estimate how many words he had generated (numerosity judgment). In the other-generated conditions, participant listened to a list of words. The number of words randomly varied between 6 and 10. To prevent participant from counting the words, he had to determine whether each heard word contains a phoneme, specified at the beginning of a trial. Immediately after the recognition task, the participant was asked to make numerosity judgments of how many words he heard. Before or after the Thought numerosity judgment task participants operated the robotic system in Sync or Async mode for 60s and then answered the FoP questionnaire. **(B)** The graph shows average word judgment accuracy (judged nr. – actual nr.) for four experimental conditions. Participants showed a general suppression of numerosity judgments for self-generated words. This self-attenuation was significantly reduced in asynchronous condition. The scatter plot shows a significant positive correlation between the numerosity judgment attenuation (Async – Sync) and FoP score. The error bars show standard errors of the mean. * $p < .05$, ** $p < .01$

4 GENERAL DISCUSSION

The importance of multisensory and sensorimotor body information for the scientific study of consciousness has been widely recognized by cognitive neuroscience in the last decade. Apart from focusing on an object of conscious perception, such as in for example the traditional field of visual consciousness, increasingly more attention has been given to study the experience of the subject, the self, of conscious perception (Blanke et al., 2015). As established in the introduction, the pre-reflective experiences (i.e. bodily self-consciousness) of embodiment and sense of agency are based on the brain mechanisms of multisensory and sensorimotor integration. In this thesis I investigated how our sense of self, in particular the sense of body ownership and sense of agency, depends on multimodal bodily signals. This was achieved through employment of experimental approaches developed by cognitive neuroscience. The first part of the present work focused on the investigation of the sense of body ownership in healthy subjects and in patients with chronic loss of sensory and motor functions of lower limbs due to a lesion to the spinal cord (**Article 1** and **2**). There, we induced conflicts between tactile information and visual feedback and observed subjective and objective changes in body ownership. In the second part of the thesis work, the participants were not anymore only passive observers during the experiment, but were interactively involved in the experiment, by first passive (**Article 3**) and then active (**Article 4**) self-administration of tactile-stimuli. As such, the experimental manipulations better resembled everyday situations, where one often is an active agent in one's environment. In the third and final part of the thesis, I presented work taking the previous approaches further and investigating how experimental multisensory and sensorimotor conflicts perturb the sense of self in healthy subjects and induce experiences that share similarities with certain symptoms observed in neurological and psychiatric disorders. We have shown that particular conflicts between bodily signals not only affect body perception and sense of agency for motor actions (**Article 5**) but also propagate to higher levels and even influence the sense of agency for mental representations in healthy subjects (**Article 6**).

Here, in the last chapter of the thesis I first summarize the main findings of the scientific articles included in the thesis and address open questions. Next, I provide a more in depth discussion and integrate the findings in a broader context of the recent cognitive neuroscience theories of bodily self-consciousness. Lastly, I end the chapter with an outlook and give suggestions for future research that could evolve from the present work.

4.1 SUMMARY OF THE MAIN RESULTS

4.1.1 PART 1: THE SENSE OF BODY OWNERSHIP

In the first article (**Article 1**), we investigated how integration of visual and tactile information related to lower limbs depends on the visuo-spatial viewpoint from which legs are seen and on their visual similarity to real human legs. We showed that the visuo-tactile integration and the sense of ownership do not only depend on the bottom-up spatio-temporal correlation between visual and tactile stimuli, but also on the top-down visual factors, such as the visuo-spatial viewpoint and corporeal similarity of the virtual legs. The current study thus extends existent findings for hands (Costantini & Haggard, 2007; Heed & Röder, 2008; Pavani et al., 2000; Tsakiris & Haggard, 2005) and the whole body (Maselli & Slater, 2014) to the lower extremities and it emphasizes the importance of an egocentric visuo-spatial reference frame for the integration of multisensory bodily signals and sense of body ownership.

A comparison between the results of the CCE task and questionnaire ratings showed that experimental factors differently affected the two measures. The observed differences raised two important questions regarding the relationship between objective (CCE) and subjective (questionnaire ratings) measures, and between multisensory integration of bodily signals and the sense of body ownership.

The performance on the crossmodal congruency task reflects how multisensory stimuli in the peripersonal space are processed and integrated (Spence, Kingstone, Shore, & Gazzaniga, 2001). Thus, the CCE changes we measured in our experiment reflect how the multisensory peripersonal space surrounding the legs was affected by the manipulation of visual top-down effects on the leg representation (i.e. viewpoint and body similarity). For this reason, the CCE cannot be directly equated with subjective sense of body ownership, measured with questionnaire ratings, although it may be modulated by the changes in body experience (Aspell et al., 2009; Maravita, Spence, Kennett, & Driver, 2002; Maselli & Slater, 2014; Pavani & Castiello, 2004; Sengul et al., 2012; Zopf, Savage, & Williams, 2010). Similar issue regarding the use of proprioceptive drift as a proxy to measure the RHI strength has been raised before, pointing out that the subjective experience of body ownership and proprioceptive recalibration might be two distinct phenomena (Makin, Holmes, & Ehrsson, 2008; Rohde, Di Luca, & Ernst, 2011).

This notion is also supported by the imaging data showing that the brain processes underlying the subjective sense of ownership only partially overlap with the processing and integration of multisensory stimuli in peripersonal space. For example, multisensory hand stimulation activates a large set of brain regions (Ehrsson, Holmes, & Passingham, 2005; Ehrsson et al., 2004; Makin et al., 2007), only some of which are also associated with the conscious experience of ownership for a rubber hand (Ehrsson et al., 2005; Ehrsson et al., 2004; Tsakiris, Hesse, Boy, Haggard, & Fink, 2007). As already discussed in the literature, integration of congruent multisensory signals is not a sufficient for the sense of body ownership. The experience of owning a body also depends on pre-existent body representations, regarding the body's appearance, structure and functions (Carruthers, 2008; Tsakiris, 2010). These internal models are in majority acquired throughout early sensory and motor experiences (Merleau-Ponty, 1962; Schütz-Bosbach et al., 2009), however, several studies suggest that some body representations are innate and genetically hard-wired. For example, newborns showed the ability to imitate adult's facial gestures within few hours after birth (Meltzoff & Moore, 1989) and individuals with congenital aplasia have experienced phantom sensations of absent limbs (Saadah & Melzack, 1994). Nevertheless, these pre-existent internal models of the body provide top-down constraints for the integration of multisensory bodily signals and self-attribution of a body part. The interactive effect of multisensory congruence and pre-existent body models on the sense of body ownership in fact ensures that the sensory signals from external objects are not as easily integrated with bodily signals and external objects perceived as belonging to one's body. As such, the interaction between bottom-up sensory signals and top-down factors enables on one hand to continuously process and update the state of one's body, which is essential to avoid potentially harmful stimuli in the environment, while on the other hand, provides a stable and continuous perception of the body as unity, and it enables its distinction from other bodies or objects.

In the follow-up study (**Article 2**) we have adapted the VLI paradigm to test the sense of leg ownership in the SCI patients with paraplegia. We found that on average SCI patients experienced illusory leg ownership less strongly than their age- and gender-matched controls. Contrary to our findings, one would expect that SCI-patients would depend stronger on provided visual information (regarding lower limbs) due to impaired or complete loss of tactile and proprioceptive signals from the legs (for reviews on multisensory integration see: Deneve & Pouget, 2004; Ernst & Bülthoff, 2004), and be consequently more prone to incorporate dummy legs as their own. However, our results suggest that, in the SCI patients, the top-down effect of off-line visual leg representation critically modulates multisensory integration during the illusion. Throughout the time, prolonged sensorimotor deprivation probably induced stronger reliance on the new internal body model (modified by the injury) than on actual, on-line sensory signals. This notion is further supported by our correlation analyses, showing that the intensity of illusory ownership decreased with time since injury. Similar findings were also observed in arm amputees, who showed weaker effects of the RHI with longer time since amputation (Ehrsson et al., 2008).

We also investigated whether applying tactile stimulation just above the lesion site would result in stronger indices of the illusion as compared to the stimulation of a more distant, control site on the back. Such an effect would indicate functional somatotopic reorganization in the primary somatosensory cortex, as it was previously observed in stroke patients, amputees and patients with spinal cord injury (Aglioti, Bonazzi, & Cortese, 1994; Moore et al., 2000; Ramachandran & Hirstein, 1998; Ramachandran, Stewart, & Rogers-Ramachandran, 1992; Rivers & Head, 1908; Scandola et al., 2014; Turton & Butler, 2001). However, no effect of the body part being stimulated was found on subjective experience of the illusion. Nevertheless, the negative correlation between the time since injury and illusion ratings might indicate that SCI-related brain plasticity occurs during the course of prolonged sensorimotor deprivation, most probably in the multimodal brain areas (and their connections) related to body processing, such as the vPMC, posterior parietal cortex, and insula (Serino et al., 2013). In addition, the SCI patients did not differ from healthy participants in their experience of the FBI, where, in contrast to the VLI, the visual stimuli were applied to the upper trunk where sensory functions were fully preserved. Thus, with the presence of afferent signals, the basic multisensory mechanisms necessary for generating a coherent sense of global body ownership were not altered.

We also investigated possible analgesic effects of the VLI and FBI paradigm on the perception of neuropathic pain. One of the mechanisms proposed to explain neuropathic pain in patients with chronic deinnervation is the incongruence between visual feedback, tactile, and proprioceptive signals (Ramachandran & Altschuler, 2009; Schmalzl, Ragnö, & Ehrsson, 2013). Such mismatch can be transiently corrected by providing illusory tactile perception, which might temporarily activate otherwise silent cortical regions, previously receiving tactile input from now deinnervated body parts (Schmalzl et al., 2013). Our data showed a marginally significant analgesic effect in the VLI, during the synchronous visuo-tactile stimulation of the lower back (and virtual legs). We speculate that this particular experimental manipulation might have activated the cortical regions that were previously representing lower limbs through the induction of illusory tactile sensations. Similar analgesic effects of the RHI have also been reported in upper limbs amputees (Schmalzl et al., 2013). On contrary, we found an overall reduction in perceived neuropathic pain in the FBI, regardless of the experimental condition. This effect could be due to the analgesic effect of seeing own body, as previous studies showed that visual feedback of own body reduces the perception of painful stimuli (Longo, Betti, Aglioti, & Haggard, 2009; Mancini, Longo, Kammers, & Haggard, 2011; Romano et al., 2016). Alternative, but not exclusive explanation for the general pain reduction during the FBI experiment might be that the setup itself served as a distraction from pain, an effect previously associated with immersion in virtual reality and video games (Triberti, Repetto, & Riva, 2014).

Although the mechanisms described above might have jointly contributed to the pain reduction observed in our study, further investigation is needed to better understand how the body illusions work in reducing the pain. Nevertheless, these findings can be relevant for planning of neurorehabilitation and pain management protocols in the SCI patients, as the intervention might be the most effective when used early, before long-term brain plasticity occurs.

Certain limitations of the current study should be addressed in the follow-up research, such as greater homogeneity of the SCI sample in terms of lesion level and degree of sensorimotor impairment, longer duration of experimental stimulation, more automatized and controlled means of delivering multisensory stimulation, and the use of objective measures to assess changes in body and pain perception. Future work should also explore whether the brain areas (and their connections), previously linked to the body processing and subjective experience of body ownership (Serino et al., 2013) are affected by the SCI-related structural and functional reorganization. Finally, one would aspire to see short- and long-term effects of such multisensory body illusion paradigm at neural levels in the SCI patients.

4.1.2 PART 2: SELF-TOUCH

The second part of the thesis has focused on the role of self-administered tactile stimulation (self-touch) in the integration of multisensory and sensorimotor signals and related subjective experiences of self-touch, hand ownership and hand location in the peripersonal space. We first explored how manipulating proprioceptive signals by crossing the hands affects the experience of illusory self-touch in the tactile RHI, where self-touch was passive (administered by the experimenter), and hand ownership in the classic, visual RHI (**Article 3**). We showed that the illusion of self-touch in the tactile RHI was enhanced by crossing the hands, and that such increase is not due to unfamiliar hand posture, and that it occurs regardless where in the peripersonal space the hands are crossed.

These findings are important to understand how the brain constructs the presentation of own body and the space surrounding it, based on the available multisensory input. In the absence of visual information, as it was the case in our tactile RHI paradigm, the inference regarding the location of tactile event relies solely on the tactile and proprioceptive signals. Self-touch, however, provides salient information about the structure and location of the body, as it involves tactile inputs from the touch-administrating and from the touch-receiving body part, as well as proprioceptive signals (Frédérique de Vignemont, Ehrsson, & Haggard, 2005; Merleau-Ponty, 1962; Schütz-Bosbach et al., 2009; van Stralen et al., 2011).

Normally, the double-tactile stimulation during self-touch is perceptually inseparable (touchant-touché, Merleau-Ponty, 1962). However, separating this otherwise unitary tactile percept is possible through perceptual illusion. The tactile RHI (Ehrsson et al., 2005) enables to investigate how the brain integrates and gives rise to a single tactile sensation (i.e. self-touch) through interaction between two spatially separated, but temporally matched tactile stimuli and proprioception signals. The self-touch illusion is experienced due to the inference based on the probability that if two tactile stimuli are perceived synchronously, they must refer to the same tactile event (Petkova, Zetterberg, & Ehrsson, 2012; Ramachandran & Hirstein, 1998). This perceptual inference is however constrained by proprioceptive signals. For example, if the spatial separation between the hands becomes too large, the illusion is abolished (Aimola Davies et al., 2013). Here we tried to influence the tactile-proprioceptive integration during self-touch illusion by making proprioceptive signals noisier, through postural manipulation of hand crossing. Abundance of studies show that such postural manipulation reduces the accuracy of proprioceptive signals and impairs tactile localization (Holmes et al., 2006; Medina & Coslett, 2010; Shore et al., 2002; Charles Spence et al., 2004; Yamamoto & Kitazawa, 2001). Our findings indicate that crossing the hands introduced an additional bias in the weighting of tactile and proprioceptive signals, when no visual information about the position of the hands was available. Consequently, this increased the probability that two spatially separated, but temporally synchronized, tactile stimuli are interpreted as occurring at a single spatial location, resulting in recalibration of proprioceptive sense and enhanced subjective experience of self-touch. No such crossed-hand effect was observed in the classic, visual version of the RHI, during which the visual information about the position of the hands was available. Indeed, as vision provides the best spatial resolution amongst the senses, it usually biases tactile and proprioceptive perception (Ernst & Bülthoff, 2004; Graziano, Cooke, & Taylor, 2000; Spence, Pavani, & Driver, 2000). Thus, seeing the rubber hand being touched annulated any boosting effect of hand crossing in the experience of the visual RHI.

The results of the present study demonstrate how the brain's mechanisms of perceptual inference regarding own body can be studied through relatively simple somatosensory illusion. It provides evidence for the processes of weighting and integrating sensory inputs based on current availability and existent priors, underlying our experiences of the bodily self.

The sense of body ownership has been widely studied by using body illusions where conflicting multisensory information is used to induce illusory self-attribution of a whole body or body part

Blanke et al., 2015; Blanke, 2012; Botvinick & Cohen, 1998; Ehrsson et al., 2005; Tsakiris & Haggard, 2005). Importantly, these studies focused on the role of afferent signals in the sense of body ownership. On the other hand, it is well established that efferent signals provide an important contribution to the bodily self-consciousness via voluntary action and sense of agency (Blakemore, Frith, & Wolpert, 1999; David, Newen, & Vogeley, 2008; Tsakiris et al., 2006; Wolpert & Ghahramani, 1995). We here further studied how additional motor signals during voluntary self-touch influence the integration of bodily signals and affect the subjective experience of illusory self-touch and hand ownership (**Article 4**). This was achieved by using a custom-built robotic system (as described in Section 1.3.2), which allowed the participants to actively touch a virtual hand, while the robot applied the same tactile stimuli to participant's other hand. We showed that the presence of efferent signals increased the illusion of self-touch and the sense of ownership for the virtual hand. These results indicate that not only the integration between afferent signals alone contributes to the sense of ownership (Blanke et al., 2015; Blanke, 2012; Botvinick & Cohen, 1998; Ehrsson et al., 2005; Tsakiris & Haggard, 2005), but also that correspondence between efferent signals and afferent multisensory feedback enhances the self-attribution of the virtual hand.

These findings support the view that the sense of body ownership occurs through constant updating of sensory predictions based on the available sensory input from the environment in order to minimalize prediction error and enable optimal perception (Apps & Tsakiris, 2014; Clark, 2013). Thus, combining various sensory inputs usually enables better estimation of the state of own body and its immediate environment. The presence of efferent signals through active self-touch provided additional sensory evidence to the predictions and further minimalized the error. In other words, when tactile and visual feedback matched the expected outcome (based on the executed movement), the sensorimotor correspondence was increased, and consequently self-attribution of the virtual hand stronger. Our results accord with the proposition that the sense of agency importantly contributes to the experience of body ownership by providing additional source of information to the process of self-attribution and self-recognition (Schütz-Bosbach et al., 2009; Tsakiris et al., 2006; Tsakiris, Schütz-Bosbach, & Gallagher, 2007). The present findings are also relevant for the understanding and treatment of certain neurological conditions, where the sense of body ownership is compromised. For example, it was shown that self-touch enhances tactile processing and restores impaired structural body representation in patients with unilateral tactile extinction or neglect (Coslett & Lie, 2004; Valentini et al., 2008; van Stralen et al., 2011; Weiskrantz & Zhang, 1987). Thus, combining afferent and efferent signals through a controlled robotic stimulation might in future constitute a therapy aiming at restoration of bodily self-consciousness in this clinical population.

4.1.3 PART 3: THE SENSE OF AGENCY AND DELUSIONS IN HEALTHY SUBJECTS

The third part of the thesis has focused on the relationship between multisensory and sensorimotor integration and abnormal self-experiences. In particular, we investigated how specific temporal and spatial conflicts between efferent motor signals and afferent proprioceptive and tactile feedback contribute to abnormal perception of self in healthy subjects. In **Article 5** we showed that experimentally injecting a temporal delay between motor signals and tactile feedback via the robotic system (Section 1.3.2) not only resulted in reduced sense of agency, but also induced the feeling to be in the presence of another agent (FoP).

Explained in the view of predictive coding theories, our experimental manipulation perturbed the congruence between sensorimotor predictions about the sensory consequences of movement and actual feedback signals. This particular spatio-temporal mismatch caused misperception of the source and identity of own sensorimotor signals. This resulted in the illusion of being in the presence of another agent. In addition, in the same study we performed lesion analyses of neurological patients with the FoP. We showed that the FoP was associated with specific sensorimotor deficits and with fronto-parietal, temporo-parietal and insular lesions. We postulate that alterations in the congruency between sensorimotor predictions and feedback signals - due to brain lesions or appropriate experimental manipulations - underlie the FoP phenomenon.

The experience of the FoP has not only been observed in neuropsychiatric patients (Brugger et al., 1996), but it was also reported by healthy individuals who were in extreme environmental conditions and endured periods of physical exhaustion and isolation, such as high-altitude mountaineers and north-pole explorers (Brugger et al., 1999; Suedfeld & Mocellin, 1987). Such environments are associated with invariant sensory stimulation or deprivation, conditions that are known to induce hallucinations (Lloyd, Lewis, Payne, & Wilson, 2011). In addition, these individuals have been exposed to extremely low temperatures, low oxygen levels, physical exhaustion and solitude (Brugger et al., 1999). We speculate that such combination of the environmental and physical factors might have impacted the integration of sensorimotor signals and facilitated the occurrence of the FoP.

Certain considerations should be made with regard to the data of neurological patients and their comparisons with the results obtained from experimental investigations in healthy subjects. First, the experience of FoP, reported by healthy subjects was generally weaker than hallucinations in the neurological patients. Second, the data analysis of overlapping lesions in neurological patients needs to be considered with caution as the data have been collected with multimodal imaging techniques and include heterogeneous lesion extents and lesion etiology. In order to corroborate the present findings, the future work should test whether a similar network of brain regions observed in the patients' lesion analysis, is also associated with the illusory feeling of the FoP in healthy subjects. This should be achieved by overcoming technical challenges to combine the robotic setup with, for example, electrophysiology, transcranial magnetic stimulation, or magnetic resonance imaging.

In the subsequent study, we aimed to elucidate whether the same robot-induced sensorimotor mismatch would also affect the sense of agency for own mental representations (**Article 6**). In three separate experiments participants operated the master-slave robotic system while they performed the memory generation effect task (Experiment 1), phonetic verbal fluency task (Experiment 2) or word numerosity judgment task (Experiment 3). We showed that performing the tasks in the condition with the delay between one's movements and received tactile feedback, impaired the recognition of self-generated associations and reduced subjective sense of agency for the self-produced words. The same experimental condition also increased the subjective ratings of thought influencing and thought insertion, the two experiences characteristic for schizophrenia (American Psychiatric Association, 2000; Mellor, 1970; Schneider, 1959). Lastly, we also showed that participants judged to have generated more words in the FoP-inducing than synchronous condition. The performance on the two tasks as well as the subjective ratings of thought insertion positively correlated with the strength of experienced FoP. Together, these results show that experimental perturbation of sensorimotor integration not only reduces the sense of agency for motor actions and their sensory consequences (David et al., 2008; Gallagher, 2000; Jeannerod, 2003; Pacherie, 2008; Tsakiris et al., 2006), but also affects how we construct the authorship for the actions that lack accompanying efference copies or sensory consequences, such as thoughts.

These results support and provide experimental evidence for the theoretical perspective of hierarchical predictive coding for the sense of self (Apps & Tsakiris, 2014; Clark, 2013), which claims that our representation of the world is constructed through an ongoing interaction between bottom-up sensory inputs and top-down predictions, or prior beliefs.

In this line of reasoning, a prediction error induced through robotically induced sensorimotor mismatch led to the cognitive misinterpretations of the causality of the sensory event, i.e. the loss agency, and to the belief formation that "someone else is standing behind and touching the back". This belief, in turn, reinforced the perceived dissociation between own movements and the received tactile feedback that, we speculate, furthermore strengthened the delusional belief, propagating to the degree where subjects experienced their thoughts as being influenced or inserted by an external agent.

These findings contribute to the understanding of the relationship between aberrant perception and delusion formation in everyday circumstances as well as in the view of psychopathological symptoms. Nevertheless, further research is needed to support the current findings. Would, for example, a similar sensorimotor conflict, but induced between movements and other sensory modalities (i.e. sound or vision) lead to similar delusional beliefs? Moreover, in order to provide evidence that the described mechanisms underlie the symptoms of schizophrenia, the performance of the patients with passivity symptoms outside the robotic platform should be comparable with the current results. In addition, studies providing neuroimaging data could further corroborate the current behavioral results. For example, one could expect a similar brain network to be activated during experimentally induced delusions of control in healthy subjects and during schizophrenic episodes.

4.2 SELF AND OTHERS AS PREDICTIONS

The research presented in this thesis has shown that the fundamental aspects of the sense of self importantly depend on the integration of multisensory and sensorimotor signals. We showed that, according to the general laws of multisensory integration (Stein & Stanford, 2008) and its constraints for body stimuli (Blanke et al., 2015), temporally matched multisensory and sensorimotor inputs increased the sense of ownership for a rubber or virtual hand, legs and whole body, induced the illusory sensation that one is touching one's own body, and boosted the sense of agency for the source of tactile stimulation. In general, these findings accord well with the existent theories of multisensory foundations of bodily self-consciousness (Blanke & Metzinger, 2009; Blanke et al., 2015; Blanke, 2012; Maravita, Spence, & Driver, 2003; Serino et al., 2013; Tsakiris & Haggard, 2005; Tsakiris, Hesse, et al., 2007). However, the work in this thesis also shows that the bodily self is not only constructed on the basis of bottom-up sensory signals but it is modulated by top-down influences, such as pre-existent representations or models we have about our body (Carruthers, 2008; Tsakiris, 2010). For example, we showed that the strength of leg ownership was greatly modulated by the visuo-spatial viewpoint from which the legs were seen, and by their visual anatomical resemblance to real human legs. Also, as observed in SCI patients, a body schema, which is altered through a course of chronic sensorimotor deinnervation of legs, influences the integration of visuo-tactile stimuli and reduces the ownership for virtual legs. Top-down modulation is also observed in the illusion of self-touch; we have learnt through everyday experience of self-touch that when the hand moves to touch our body, and the touch is consequently felt at two locations at the same time, there is a high probability we are actually touching our body. Conversely, these experiences also dictate that if our hand has not moved immediately before we felt the touch, it must have been something or someone else that touched us.

Thus, how we perceive or body and ourselves as agents in the environment depends on mutual interactions between the multimodal sensory inputs and the prior models or predictions we have about the respective sensory event. In the framework of predictive coding theories (Apps & Tsakiris, 2014; Clark, 2013; Friston et al., 2006), our predictions about the world (and our body) modulate our perception, and in case of their mismatch, a prediction error is signaled and the model (prediction) we have is updated. Through a process of constant feedforward and feedback communication between perception and multiple levels of predictions we therefore construct models about ourselves and our environment. As agents, we can actively seek and generate the sensory input to validate our predictions through motor actions. However, when there are disruptions in the generation of error predictions, as suggested for schizophrenia (Apps & Tsakiris, 2014; Clark, 2013; Fletcher & Frith, 2009; Friston et al., 2006), insufficient updates of the predictions can lead to abnormal interpretation of the sensory input and to consequently bidirectional reinforcement of perceptual anomalies and delusional models about the world in sort of a cascadic, self-confirming cycle.

On one hand, the self is therefore viewed as nothing more than a complex of constantly updated predictions of the bodily sensory input. However, on the other hand, it is a system that does not only react to external stimuli, but it actively predicts and seeks them, and it continuously evolves and self-corrects. Through a constant update of sensory predictions we therefore actively construct and update our knowledge about ourselves and the world in order to reduce uncertainty and surprise. We are able to distinguish our body and our own actions from others, and on the other hand, predict and understand the intentions and beliefs of others (Kilner, Friston, & Frith, 2007) which enables us to more or less successfully interact and navigate in our social environment, as well as understand and construct our culture.

The novelty of the results presented in this thesis resides, first, in the implementation of virtual reality and robotics to study the mechanisms of the sense of self. This technology allowed the manipulation of congruence between bodily signals in a controlled manner to induce bodily illusions, through which we investigated the role of multisensory and sensorimotor integration in the bodily self-consciousness. These findings thus extend the existing knowledge on the sense of body ownership and the sense of agency by demonstrating that afferent and efferent signals (and their interaction) have an essential role in the basic sense of self. Secondly, the results in this thesis advance the current understanding of how the alterations of bodily self-consciousness may affect higher order cognitive processes involved in self and other representations. Our results show that sensory conflicts between own motor signals and their sensory feedback also impaired the self-other distinction of own mental content. These findings are the first to provide experimental evidence for the role of sensorimotor signals in thought processes and link the forward models for motor agency to the thought agency. As such, these findings can significantly contribute to our current understanding of neurological and psychiatric conditions, which are characterized by impaired sense of self.

4.3 CONCLUSION AND OUTLOOK

The research work I presented in this thesis corroborates an existing body of knowledge on the bodily self-consciousness and shows that fundamental aspects of the self, i.e. the experience of being a subject in a body, and an agent of own actions, depend on the processing and integration of multisensory and motor bodily signals. However, I also show that the basic sense of self is not only driven by the bottom-up sensory input, but is modulated as well by predictions, expectations and models of sensory events. Moreover, the behavioral findings show that manipulating the multisensory information regarding one's own body does not only affect how one perceives the body and its motor actions but also influences higher levels of the self, such as the sense of agency for one's own thoughts. The self should thus not be studied as a phenomenon isolated from the body, but instead, by acknowledging its intimate link with the body, they need to be regarded as an integrated unit.

The current findings can serve as a starting point for several directions of future research. One line of work should aim at providing further behavioral evidence in support of the theoretical account and try to elucidate neural correlates of the brain's predictive coding mechanisms in the sense of self. These studies should for example address the question whether prediction signaling is based on a global, supramodal network, or whether it depends on subsets of modality specific networks.

Also, seeing humans as social creatures, one cannot circumvent the study of the self and its multisensory and sensorimotor mechanisms in the context of the social environment, which has an immense role in shaping our perception, cognition and action. Several lines of research have already addressed the important role the perception of body has in cognition, i.e embodied cognition (Borghi & Cimatti, 2010). For example, in the study of Bergouignan et al. (2014), a full body illusion was induced in a social context to study its effects on autobiographical memory. In particular, due to synchronous visuo-tactile stimulation, subjects experienced disownership of their body and participated in a social scenario as seen from a third person's visuo-spatial viewpoint. This experimental stimulation caused an episodic impairment for the events that were encoded during the body illusion. Multisensory body illusions were also shown to modulate our social perceptions and cognition and alleviate prejudices, racial biases and stereotypes (for an overview, see: Maister, Slater, Sanchez-Vives, & Tsakiris, 2015). For example, inducing an illusory ownership for a body with different racial features than one's own reduced implicit racial biases toward the other race (Peck, Seinfeld, Aglioti, & Slater, 2013). Also, in the so-called enfacement illusion (Tsakiris, 2008), a participant observes a face of a stranger's face being stroked in synchrony with his face. This illusion was shown to increase the perceived similarity and closeness toward the other and enhances conformity behavior (Paladino, Mazzurega, Pavani, & Schubert, 2010). Moreover, the studies of joint action have showed that a close link between action and perception is fundamental to form presentations and predictions of other's directed goals, be able to understand other's behavior and engage in social interactions (for a review see: Sebanz, Bekkering, & Knoblich, 2006). Thus, research in cognitive neuroscience has been increasingly focusing on the relationship between multisensory and sensorimotor processing, social interactions and the experience of the self. Hopefully, we will soon witness the emergence of new research paradigms that can be used in every-day social setups, and which could contribute to a more integrated understanding of the basis of the selfhood and its disorders.

For that reason, another line of investigation should focus on the development of the current experimental methods and robotic technologies, with the aim of making them applicable outside of the lab environment, as well as increasing their therapeutic usability. In the last few years, we have witnessed a rise in commercially available, attractive and easy-to use virtual reality goggles, as well as physiological stimulators, sensors, health and fitness trackers, in form of smart jewelry, watches and phones. Using this technology in scientific research will on one hand enable delivering experimentally controlled stimulation to the subject outside of the lab settings, and on the other hand, enable to collect a massive amount of data, which can without doubt advance our understanding of the bodily foundations of the self.

In conclusion, possessing a body, this beautiful instrument necessary for action and perception, provides a foundation and ability to perceive one's self as distinct from others. On the other hand, having the sense of self grounded within the physical boundaries of one's own body makes it possible to live and interact in the world of others.

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6 ABBREVIATIONS

RHI	rubber hand illusion
FBI	full body illusion
VLI	virtual leg illusion
HMD	head-mounted display
vPMC	ventral premotor cortex
IPS	intraparietal sulcus
fMRI	functional magnetic resonance imaging
SCI	spinal cord injury
AH	autoscopic hallucinations
OBE	out-of-body experience
HAS	heautoscopy
FoP	feeling of a presence
CCE	crossmodal congruency effect

7 APPENDIX

7.1 MOTOR IMAGERY IN SPINAL CORD INJURED PEOPLE IS MODULATED BY SOMATOTOPIC CODING, PERSPECTIVE TAKING AND POST-LESIONAL CHRONIC PAIN

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Motor imagery in spinal cord injured people is modulated by somatotopic coding, perspective taking, and post-lesional chronic pain

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Motor imagery (MI) allows one to mentally represent an action without necessarily performing it. Importantly, however, MI is profoundly influenced by the ability to actually execute actions, as demonstrated by the impairment of this ability as a consequence of lesions in motor cortices, limb amputations, movement limiting chronic pain, and spinal cord injury. Understanding MI and its deficits in patients with motor limitations is fundamentally important as development of some brain–computer interfaces and daily life strategies for coping with motor disorders are based on this ability. We explored MI in a large sample of patients with spinal cord injury (SCI) using a comprehensive battery of questionnaires to assess the ability to imagine actions from a first-person or a third-person perspective and also imagine the proprioceptive components of actions. Moreover, we correlated MI skills with personality measures and clinical variables such as the level and completeness of the lesion and the presence of chronic pain. We found that the MI deficits (1) concerned the body parts affected by deafferentation and deefferentation, (2) were present in first- but not in third-person perspectives, and (3) were more altered in the presence of chronic pain. MI is thus closely related to bodily perceptions and representations. Every attempt to devise tools and trainings aimed at improving autonomy needs to consider the cognitive changes due to the body–brain disconnection.

Motor imagery (MI) is defined as the process of internally representing a motor command without an effective overt movement as the outcome (Jackson, Lafleur, Malouin, Richards, & Doyon, 2001). However, MI is closely connected to action execution, as demonstrated by neuroimaging results showing that MI involves neural

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structures largely overlapping with those involved in actually performing the imagined movements, in particular the pre-motor areas, the left intraparietal sulcus, and subcortical structures such as basal ganglia and cerebellum (Bonda, Petrides, Frey, & Evans, 1995; Corradi-Dell'Acqua, Tomasino, & Fink, 2009; Decety, 1996; Gerardin *et al.*, 2000). As during MI actions are not actually carried out, the motor cortex shows much less activation for imagined compared to real movements (Andersen, Hwang, & Mulliken, 2010). For these reasons, MI is considered in an intermediate position along the continuum within motor preparation and motor execution (Nikulin, Hohlefeld, Jacobs, & Curio, 2008; Stephan & Frackowiak, 1996; Stephan *et al.*, 1995). The inherent link between motor imagery and action execution has been confirmed in studies, showing that MI is altered in a number of pathological conditions characterized by an impairment of the ability to actually perform actions such as locked-in syndrome (Conson *et al.*, 2008), amyotrophic lateral sclerosis (Fiori *et al.*, 2013), dystonia (Fiorio, Tinazzi, & Aglioti, 2006), and in chronic pain conditions (Coslett, Medina, Kliot, & Burkey, 2010; Schwoebel, Friedman, Duda, & Coslett, 2001).

Another clinical condition that could make the execution of some movements extremely difficult or even impossible is spinal cord injury. Sufferers cannot move body parts below the lesion level due to a massive disconnection between the brain and the body. Actual motor deficits in SCI depend on the lesion level, with cervical lesions typically inducing tetraplegia (deficits involving both upper and lower limbs) and dorsolumbar lesions inducing paraplegia (deficits involving only lower limbs).

Thus, SCI constitutes an important model for exploring the relationship between MI and the execution of specific movements. While initial research and recent behavioural results suggest that MI abilities are spared after SCI (Decety & Boisson, 1990; Hotz-Boendermaker *et al.*, 2008), neuro-functional anomalies in the dynamics of event-related potentials (Lacourse, Cohen, Lawrence, & Romero, 1999) and altered cortical activation during MI tasks have been found (Alkadhi *et al.*, 2005; Cramer, Orr, Cohen, & Lacourse, 2007; Hotz-Boendermaker *et al.*, 2008). However, whether SCI people maintain their MI ability over time and they implement new post-lesional cognitive strategies is still unclear (Fiori *et al.*, 2014; Hotz-Boendermaker *et al.*, 2008). Despite the increasing interest in this topic (Di Rienzo, Collet, Hoyek, & Guillot, 2014), no systematic studies on the effects of level and completeness of the lesion on different types of MI in SCI have been performed. Moreover, little is known about whether MI defects specifically involve the body parts that cannot be voluntarily moved and how MI deficits in SCI may be influenced by clinical variables such as the interval of time since the lesion, the degree of autonomy, and the presence of pain.

To explore these issues, we used a self-reporting measure of explicit MI (originally introduced by Isaac, Marks, & Russell, 1986) in the revised version of Roberts and colleagues (VMIQ-2, Roberts, Callow, Hardy, Markland, & Bringer, 2008). The questionnaire consists of three subscales: (1) motor imagery from a first-person perspective (Internal Visual Imagery, IVI), (2) motor imagery from a third-person perspective (External Visual Imagery, EVI), and (3) the somatosensory components of action imagery (Kinaesthetic Imagery, KIN). Each subscale supposedly explores different MI-related cognitive processes that, although interacting a great deal in daily life circumstances, may be selectively altered by the changes in brain and body representations that occur after SCI. In the modified version used in this study, MI is divided into three subscales regarding actions involving different body parts: full body (FB), the upper limbs (UL), or exclusively the head and shoulders (HS). By means of these three subscales, we will investigate the somato-topographic specificity of MI deficits. This is necessary to better understand how the different sensorimotor deficits in tetraplegia and paraplegia may affect MI.

Participants' scores in our version of the VMIQ-2 were correlated with a number of important clinical variables, including the level and completeness of the lesion, the time since lesion, the degree of independence in daily life, and the presence of pain.

Interval of time since lesion may be an important variable in MI, because an older lesion means more consolidated compensative motor strategies and neuroplastic modifications in brain areas. Similarly, we hypothesized that incomplete lesions, in contrast with complete lesions, and better degrees of autonomy may be correlated with greater MI. In fact, regularly use of a body part in everyday activities might be an important factor in terms of maintaining the ability to imagine performing an action with that body part. In addition, personality variables were carefully controlled to exclude any potential effects on subjects' responses.

Methods

Participants

Forty-nine subjects suffering from SCI in the chronic phase (>1 year, 24 affected by paraplegia and 25 affected by tetraplegia) and 24 neurologically healthy controls (age, gender, and education matched) agreed to participate in the study. The neurological level of injury (NLI) was measured by means of the American Spinal Injury Association Scale (ASIA, Kirshblum *et al.*, 2011). Incomplete lesions were estimated by means of the ASIA Impairment Scale (AIS, Ditunno, Young, Donovan, & Creasey, 1994), according to which the completeness of the lesion is scored along 5 clinical levels, depending on sparing of below lesion-level functions (A: lesion complete; B: spared sensory functions; C and D: increasing spared sensory and motor functions; and E: apparently no motor and sensorial consequences).

AIS scores were similarly distributed in the tetraplegic and paraplegic subsamples (number of patients affected by paraplegia with incomplete lesion, B: 8, C: 1, D: 3; number of patients affected by tetraplegia with incomplete lesion, B: 7, C: 3, D: 3).

The SCIM-3 scale (Spinal Cord Independence Measure III, Invernizzi *et al.*, 2010) was used to quantify the degree of autonomy in daily life activities. Patients with (1) developmental deficits; (2) a history of head injury, vascular brain lesion, or psychiatric disorders, and/or (3) mental deterioration or deficits in general cognitive abilities were not included in the study. Clinical and demographic data are reported in Table 1.

The study was approved by the local ethics committee (CEP Prot. N. 40378) and was conducted in accordance with the ethical standards of the Declaration of Helsinki (World Medical Association, 2013).

Materials and procedure

Data regarding the MI abilities of the participants were collected at their homes or in a quiet room at a Department of Rehabilitation in one 60-min session. Other clinical variables and personality traits were assessed with specific scales. The order of the questionnaires was randomized between subjects. Participants responded verbally to the questions and the examiners manually recorded the responses.

Table 1. SCI clinical and demographic data

Subject	AIS	NLI	G	Age	Ed	Hd	Job	Int	D	SCIM-3
Pc 1	A	T8	M	44	8	R	6	1		54
Pc 2	A	T7	M	48	13	R	3	4	T	75
Pc 3	A	T6	M	29	8	R	–	7	T	75
Pc 4	A	T4	M	72	5	R	6	3	T	35
Pc 5	A	T10	M	44	8	R	1	3	T	74
Pc 6	A	T9	M	43	8	R	–	3	T	71
Pc 7	A	T5	M	28	8	R	4	4	T	68
Pc 8	A	T5	M	48	8	R	–	25	T	75
Pc 9	A	T10	F	54	13	R	4	31	T	72
Pc 10	A	T3	M	34	13	R	3	2	T	71
Pc 11	A	T11	M	48	13	R	6	29	T	72
Pc 12	A	T7	M	34	8	R	–	2	T	72
Pi 1	B	T7	M	41	17	R	9	2	T	36
Pi 2	B	T3	M	25	13	R	3	10	T	76
Pi 3	B	T5	M	61	17	R	4	2	p-Sur	72
Pi 4	B	T7	F	64	8	R	R	2	p-Sur	39
Pi 5	B	T5	M	24	8	R	4	2	T	73
Pi 6	B	T11	M	39	17	R	2	17	T	73
Pi 7	C	L2	M	50	13	R	3	27	T	73
Pi 8	D	L3	M	26	8	R	–	2	T	89
Pi 9	D	L3	M	34	8	R	6	9	T	100
Pi 10	B	L2	M	46	8	R	4	29	T	75
Pi 11	B	L1	M	42	8	R	–	8	T	60
Pi 12	D	L3	F	42	13	R	3	23	T	100
Tc 1	A	C5	F	30	8	R	4	15	T	15
Tc 2	A	C4	M	72	5	R	R	3	T	15
Tc 3	A	C5	M	46	8	R	6	1	T	24
Tc 4	A	C5	M	30	17	R	3	12	T	48
Tc 5	A	C7	M	44	13	R	4	27	T	54
Tc 6	A	C7	M	37	17	R	3	12	T	64
Tc 7	A	C5	M	63	13	R	1	44	T	63
Tc 8	A	C7	M	39	8	R	6	8	T	67
Tc 9	A	C4	M	51	8	R	–	33	T	19
Tc 10	A	C7	M	45	8	R	4	27	T	67
Tc 11	A	C7	M	39	17	R	4	8	T	50
Tc 12	A	C4	M	43	17	R	2	16	T	15
Ti 1	B	C6	M	29	13	R	–	7	T	47
Ti 2	B	C5	M	48	8	R	–	1	T	61
Ti 3	D	C5	M	41	8	R	–	3	T	85
Ti 4	D	C4	M	21	13	R	–	6	T	99
Ti 5	B	C7	M	37	13	R	–	18	T	74
Ti 6	C	C6	M	20	13	R	S	6	T	66
Ti 7	D	C6	M	57	8	R	8	6	T	99
Ti 8	B	C5	F	54	13	R	R	14	T	31
Ti 9	B	C5	M	26	13	R	–	24	T	75
Ti 10	B	C7	M	55	17	R	R	13	T	58

Continued

Table 1. (*Continued*)

Subject	AIS	NLI	G	Age	Ed	Hd	Job	Int	D	SCIM-3
Ti 11	B	C5	M	34	13	R	3	11	T	67
Ti 12	C	C6	F	40	13	R	–	23	T	75
Ti 13	C	C5	F	55	13	R	–	29	T	67

Pc = complete paraplegia (AIS = A); Pi = incomplete paraplegia; Tc = complete tetraplegia (AIS = A); Ti = incomplete tetraplegia; AIS = Asia Impairment Scale; NLI = neurological level of injury; G = gender; Ed = education; Hd = handedness (R = right); job = numbers correspond to the job categories of the ISTAT (Italian National Institute of Statistic): 1: managers, 2: intellectual and scientific jobs, 3: technical jobs; 4: secretarial jobs, 5: commercial jobs, 6: artisans, specialized workers, and farmers; 7: industrial workers; 8: unskilled jobs; 9: armed forces; R: retired; - = unemployed; Int = interval from lesion in years; D = damage; T = traumatic; p-Sur = post-Surgery; SCIM-3 = spinal cord independence measure, ranging from a minimum of 0 (complete dependence) to a maximum of 100 (complete independence).

Explicit motor imagery

Unlike that in the original VMIQ-2 version (Isaac *et al.*, 1986), the items in the revised scale (Roberts *et al.*, 2008) all require participants to imagine themselves (and not other people) while they perform actions (Roberts *et al.*, 2008). In the scale that we adopted therefore, MI was from both the first- and third-person perspectives. More specifically, the EVI subscale necessitates imagining oneself performing actions from a third-person perspective ('as if you were watching yourself from an external position').

This is a process that has been shown to involve cognitive processes other than those involved in first-person perspective imagery (Ionta, Fourkas, & Aglioti, 2010; Ionta, Fourkas, Fiorio, & Aglioti, 2007; Moro, Pernigo, Zapparoli, Cordioli, & Aglioti, 2011). For the IVI and KIN subscales, participants were asked to imagine themselves performing actions from a first-person perspective. IVI explores individuals' ability to judge an action while 'looking out through their own eyes', and for the KIN, participants must 'imagine feeling themselves doing the movement'. IVI and KIN have been identified as separate modalities (Fourkas, Ionta, & Aglioti, 2006), with the latter probably being the most sensitive measure of MI. Thus, to explore the issue of whether MI deficits are associated with action execution deficits and in order to have somatotopographic MI assessments, we made an important change to the VMIQ-2 (see Supplementary Materials) consisting of the addition of questions specifically assessing the imagery of actions performed with upper limbs, lower limbs, or both. More specifically, we asked participants to imagine actions involving (1) movements of the head, mouth, and shoulders or that consisted of maintaining assisted positions (head and shoulder actions – HS, n. 6, all new items) – the SCI patients were able to execute all of these movements; (2) movements of trunk and upper limbs (Upper Limbs actions – UL, n.3, 2 new items) – the execution of these movements was impaired in tetraplegic but not in paraplegic subjects; (3) movements of full body and/or the lower limbs (full-body actions – FB, n. 11, no new items) – the execution of these movements was impaired in all of the SCI subjects.

As in the original version, the vividness of each action image was assessed on a 5-point Likert scale (Table 2, higher value = greater difficulty in MI) and the EVI, IVI, and KIN subscales were used.

As a result of our changes in the scale, it was not possible to compare the SCI scores with the normative data (Roberts *et al.*, 2008). For this reason, a control group of neurologically healthy subjects was used.

Table 2. VMIQ-2 scores

	SCI	C	P	T
IVI				
FB	**25.9 ± 14**	16.17 ± 8.05	22.54 ± 14.31	**29.26 ± 13.53**
UL	4.58 ± 2.22	4.26 ± 2.49	3.96 ± 1.63	5.18 ± 2.57
HS	7.81 ± 3.74	9.13 ± 5.33	7.12 ± 2.25	8.46 ± 4.72
EVI				
FB	23.73 ± 13.87	17.43 ± 9.41	20.08 ± 11.40	27.24 ± 15.31
UL	4.39 ± 2.41	4.09 ± 1.88	3.79 ± 1.35	4.96 ± 3.03
HS	8.10 ± 4.53	9.35 ± 5.69	7.12 ± 2.19	9.04 ± 5.88
KIN				
FB	**26.39 ± 13.8**	15.87 ± 8.01	23.12 ± 12.69	**29.52 ± 14.38**
UL	4.37 ± 2.45	3.74 ± 1.51	3.58 ± 1.35	5.12 ± 3.02
HS	7.73 ± 3.66	8.04 ± 4.24	7.42 ± 2.87	8.04 ± 4.32

Mean ± standard deviation for the modified VMIQ-2 scale, divided by group (SCI = spinal cord injury, C = control, P = paraplegic, T = tetraplegic), subscale (IVI = Internal Visual Imagery, EVI = External Visual Imagery, KIN = Kinaesthetic Motor Imagery), and body area (FB = lower limbs and full body, range: 55-11; UL = trunk and upper limbs, range: 30-6; HS = mouth, head and shoulders, range: 15-3). Higher values mean greater difficulty in MI. The SCI group is further divided into P and T subgroups. The values, which are significantly different from the C group, are shown in bold.

Pain

To ascertain the presence of pain, a new scale inspired by the McGill Pain Questionnaire was employed (Melzack, 1987). To the best of our knowledge, this is the first scale devised to measure neuropathic, neuromuscular, and visceral pain (Supplementary Materials). The validation process is currently underway, but the preliminary results here collected, from both SCI and healthy participants, confirm its high correlation with both the *Brief Pain Inventory* (BFI, Caraceni *et al.*, 1996) and the *Douleur Neuropathique 4 Questions Scale* (Bouhassira *et al.*, 2005) (Spearman's $\rho = .46$ and .74, respectively).

Personality variables

To check the potential effects of variables linked to personality traits, the 10-item version of the Big Five Inventory Scale (BFI 10, Rammstedt & John, 2007) was proposed. In addition, potential influences of a subjective disposition towards episodes of suggestibility or absorption were assessed (Tellegen Absorption Scale – TAS, Tellegen & Atkinson, 1974). Finally, a measure of an individual disposition to accept changes in body form and surface was recorded by means of the Trinity Assessment of Body Plasticity (BodyTAP, Desmond, Horgan, & MacLachlan, 2001). As an Italian version of these instruments is not available, a back translation was used.

Data handling and statistical analyses

The VMIQ-2 responses relating to each condition (IVI, EVI, and KIN) and somatotopographic action type (FB, UL, and HS) were summed. Data from our pain subscales (visceral, neuropathic, and neuromuscular pain) were treated as categorical factors indicating the presence or absence of pain. For each interview regarding personality traits, the specific methodology of scoring according to their original version was followed.

Completeness of lesions was considered a categorical factor (absence/presence), and an integer from 1 to 30 (corresponding to intervals from the C1 to the S5 segments) was calculated for the neurological level of injury (NLI). The time from lesion onset referred to the number of years, which had passed since the injury (range: 1–44).

The analyses were all computed via the R framework for statistical analyses (R Core Team, 2015). We used the *ggplot2* package (Wickham, 2009) for graphical representations and the *coin* package (Hothorn, Hornik, van de Wiel, & Zeileis, 2006) to compute the r effect sizes for the Mann–Whitney and Wilcoxon tests.

Comparisons between the control and SCI groups were carried out for motor imagery, personality traits (Mann–Whitney tests, with the r index as effect size – small: $.1 \leq |r| < .3$, medium: $.3 \leq |r| < .5$, large: $|r|$ $.5$), and clinical data (t-test, using the Cohen's d as effect size – small: $.2 \leq d < .5$, medium: $.5 \leq d < .8$, large: $d \geq .8$; and chi-square tests, using odds ratio (OR) as effect size – small: $1.5 \leq \mathrm{OR} < 3.5$ or $0.29 < \mathrm{OR} \leq 0.67$, medium: $\mathrm{OR} \geq 3.5 \leq \mathrm{OR} < 9$ or $0.11 < \mathrm{OR} \leq 0.29$, large: $\mathrm{OR} \geq 9$ or $\mathrm{OR} \leq 0.11$).

To further investigate specific aspects of imagery (EVI, IVI, and KIN) and topography (UL, FB, and HS) within each group, 3 Friedman ANOVAs on MI questionnaire scores (Bonferroni corrected) were used for each group. Where necessary, *post-hoc* testing was carried out by means of Wilcoxon tests (Bonferroni corrected).

Moreover, the presence of any correlative link between motor imagery and clinical SCI-related variables, pain, and personality traits was verified by means of ANCOVA tests executed on the scores of the VMIQ-2 subscales (IVI, EVI, and KIN) for each action category (FB, HS, and UL). For main and interaction effects, the η^2 was used as effect size (small: $.13 > \eta^2 \geq .02$, medium: $.26 > \eta^2 \geq .13$, large: $\eta^2 \geq .26$; Miles & Shevlin, 2001). *Post-hoc* analyses were computed by means of t-tests or additional regression analyses (Bonferroni corrected).

However, to avoid confounding effects due to small groups, results involving subgroups <15 participants were discarded.

Results

The comparison between healthy control (C) and SCI groups

The two groups did not differ in age (C: 40.9 ± 14.7; SCI: 43.04 ± 12.5; $t_{(70)} = .647$, $p = .52$, $d = .16$), education ($W = 471.5$, $p = .236$, $r = .14$), and gender ($\chi^2_{(1)} = 2.84$, $p = .09$, $\mathrm{OR} = .31$).

Vividness of motor imagery

MI of FB action, as assessed by the VMIQ-2, was worse in SCI than in C in the two-first-person perception subscales: IVI-FB ($W = 798.5$, $p = .0039$, $r = .34$) and KIN-FB ($W = 833$, $p = .001$, $r = .39$). By dividing the SCI group into patients with paraplegia ($n = 24$) and patients with tetraplegia ($n = 25$), we found that the latter but not the former group significantly differed from the controls (IVI-FB: $W = 121.5$, $p = .0016$, Bonferroni corrected, $r = -.50$; KIN-FB: $W = 123.5$, $p = .0018$, Bonferroni corrected, $r = -.50$) (see Figure 1).

In contrast, in the EVI-FB subscale the difference between SCI and C was not significant ($W = 700.5$, $p = .0928$, $r = .20$) (see Figure 1).

The two groups showed similar scores in the upper body- and head/shoulder-related questions. Mean and SD in the VMIQ-2 scores are reported in Table 2.

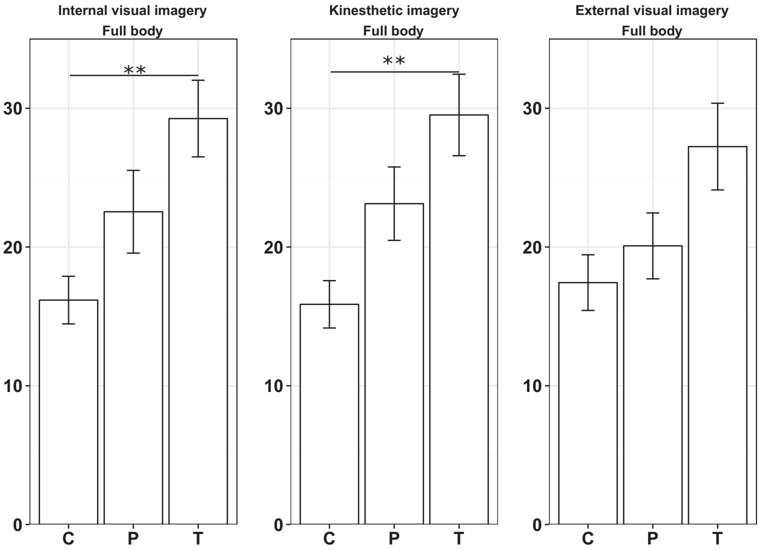

Figure 1. Full-body actions imagery. The mean and standard errors for VMIQ-2 scores relating to IVI-FB, KIN-FB, and EVI-FB scores are reported for each group. Higher values mean greater difficulty in MI. $^{**}p < .01$; C: control group, P: paraplegic subgroup, T: tetraplegic subgroup.

Differences in imagining movements of different body parts. The scores related to the three body part-related questions in the modified VMIQ-2 have different ranges (FB: from 55 to 11; UL: from 30 to 6; HS: from 15 to 3). Therefore, to allow comparisons between body parts, these scores were scaled from 0 to 1 (see equation below).

$$\text{scaled score} = \frac{\text{score} - \text{min}}{\text{max} - \text{min}}$$

The control group scores did not differ for body part (all ps > .11), confirming that the three body part questions are of equal difficulty.

First-person subscale – IVI subscale: In the *IVI subscale*, paraplegics showed differences between FB (.26 ± .32), UL (.08 ± .14) and HS (.05 ± .09) (Friedman $\chi^2_{(2)} = 11.18, p = .011$, Bonferroni corrected). *Post-hoc* tests indicate that the difference is significant between IVI-FB and IVI-HS ($U = 2$, $p = .01$ Bonferroni corrected, $r = -.57$).

There was also a difference for tetraplegics due to action topography (Friedman $\chi^2_{(2)} = 24.33$, $p < .001$, Bonferroni corrected). Nevertheless, *post-hoc* tests show that tetraplegic patients had more difficulties imagining full-body motor actions from their internal visual perspective (IVI-FB:.41 ± 31) with respect to both IVI-UL (.18 ± .21, $U = 8$, $p = .001$, Bonferroni corrected, $r = -.77$) and IVI-HS (.10 ± .20, $U = 205$, $p = .0178$, Bonferroni corrected, $r = -.77$).

Third-person subscale – EVI subscale: In the *EVI subscale*, the scores for the three types of action were significantly different in both paraplegics (Friedman $\chi^2_{(2)} = 11.15$, $p = .012$, Bonferroni corrected) and tetraplegics (Friedman $\chi^2_{(2)} = 22.44$, $p < .001$, Bonferroni corrected). Again, through *post-hoc* tests we observe that for patients with paraplegia, EVI-FB actions (.21 ± .26) were more difficult to imagine than HS ones (.05 ± .09) ($U = 9, p = .037$, Bonferroni corrected, $r = -.48$). For tetraplegics, the FB

(.26 ± .37) actions were harder than both EVI-UL (.11 ± .16, $U = 176$, $p = .011$, $r = -.50$) and EVI-HS (.09 ± .13, $U = 14$, $p = .006$, $r = -.57$).

First-person kinaesthetic subscale – KIN subscale: Finally, in the KIN subscale the results indicate the same trend. There were differences in the patients with paraplegia scores depending on the bodily area (Friedman $\chi^2_{(2)} = 15.08$, $p = .0002$ Bonferroni corrected). In particular, *post-hoc* tests show that FB scores (.27 ± .29) were worse than UL scores (.05 ± .11, $U = 156$, $p = .02$ Bonferroni corrected, $r = -.76$). For tetraplegics, KIN scores differed (Friedman $\chi^2_{(2)} = 26.05$, $p < .001$ Bonferroni corrected) and the KIN-FB scores (.42 ± .33) were worse than KIN-UL (.18 ± .25, $U = 208$, $p = .012$, $r = -.58$) and KIN-HS scores (.08 ± .18, $U = 7$, $p = .001$, $r = -.80$) (Figure 2).

Personality traits

The scores of the SCI and C groups did not differ in either the Tellegen Absorption Scale (Tellegen & Atkinson, 1974) (C: 40.3 ± 15.87; SCI: 33.02 ± 16.3; $W = 419$, $p > .08$, $r = .2$) or the Trinity Assessment of Body Plasticity (Desmond *et al.*, 2001) (C: 66.6 ± 9.28; SCI: 68.8 ± 13; $W = 559$, $p = .67$, $r = .05$). In the Big Five Inventory (Rammstedt & John, 2007), only the Extraversion subscale showed a difference between the groups, with SCI showing greater extroversion than controls ($W = 779.5$, $p < .01$, $r = .31$, SCI group = 7.49 ± 1.76; control group = 6.13 ± 1.98). By further dividing the SCI group into Tetraplegia (T: 7.72 ± 1.88) and Paraplegia (P: 7.25 ± 1.62), only the T group showed to be more extrovert than the C ($W = 163.5$, $p = .029$, Bonferroni corrected, $r = -.38$) by means of *post-hoc* tests.

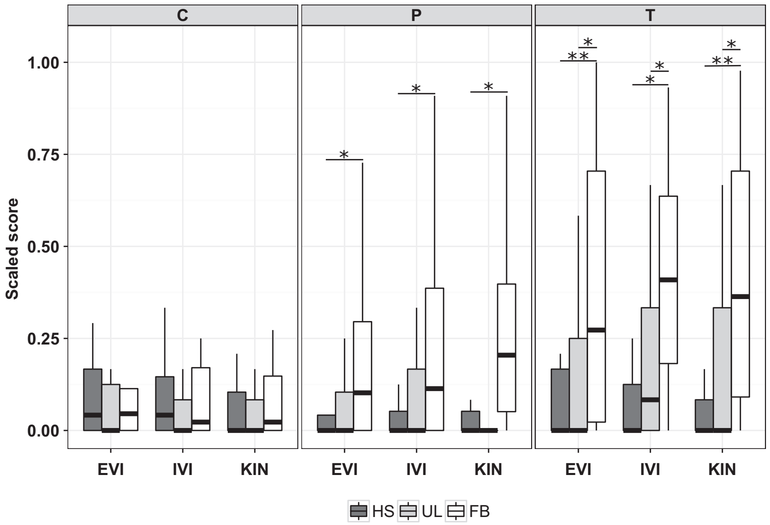

Figure 2. Scaled scores in the modified VMIQ-2. Scores are divided for groups (C: control group, P: paraplegic subgroup, T: tetraplegic subgroup), subscales (EVI: External Visual Imagery, IVI: Internal Visual Imagery, KIN: Kinaesthetic Imagery), and body parts (HS: mouth, head, shoulders, UL: trunk and upper limbs, FB: lower limbs and full body). The central line represents the median, the top and the bottom of the box are the first and third quartiles, and the whiskers are the interquartile range of the lower quartile and of the upper quartile multiplied by 1.5. $^*p < .05$, $^{**}p < .01$.

Pain

The two subgroups of SCI subjects reported neuropathic pain more frequently than controls (C = 4.35%; SCI = 57.14%, $\chi^2_{(1)} = 16.01$, $p < .001$, OR = 29.33; tetraplegics: 52%, $\chi^2_{(1)} = 10.96$, $p < .001$ Bonferroni corrected, OR = 23.83; paraplegics: 62.5%, $\chi^2_{(1)} = 15.19$, $p < .001$ Bonferroni corrected, OR = 36.67). The difference between the paraplegics and the tetraplegics was not significant ($\chi^2_{(1)} = 0.21$, $p = .65$, OR = .65). The number of people reporting musculoskeletal pain did not differ across the groups (C = 47.82%, SCI = 40.81%, $\chi^2_{(1)} = 0.09$, $p = .76$, OR = 0.75).

Moreover, in the control group nobody reported visceral pain, while 10 participants in the SCI group reported this type of pain (C = 0%, SCI = 20%, $\chi^2_{(1)} = 3.88$, $p < .05$). There was no statistically significant difference between the tetraplegic and paraplegic subgroups for the frequency of visceral pain (16% vs. 25%).

By comparing the pain sensations within the SCI group, we found a difference of frequency among neuropathic, visceral, and musculoskeletal pain ($\chi^2_{(2)} = 13.897$, $p < .001$, OR = 2.69). *Post-hoc* tests show that the difference between visceral and neuropathic pain is significant (20% vs. 57%, $\chi^2_{(1)} = 12.422$, $p = .001$ Bonferroni corrected, OR = 5.2), while the differences between visceral and musculoskeletal pain (20% vs. 41%, $\chi^2_{(1)} = 3.891$, $p = .14$ Bonferroni corrected, OR = 2.69) and between neuropathic vs musculoskeletal pain ($\chi^2_{(1)} = 2.001$, $p = .63$ Bonferroni corrected, OR = 1.93) are not.

Effects of clinical variables

Full-body motor imagery

A significant effect of the NLI was found in the IVI-FB subscale, $F_{(1,\ 26)} = 6.67$, $p = .037$, $\eta^2 = .16$, indicating that lesions at higher levels were associated with worse performance (Figure 3).

The interaction between musculoskeletal pain and the interval from the lesion onset was significant in EVI-FB, $F_{(1,\ 26)} = 4.91$, $p = .036$, $\eta^2 = .16$ and in KIN-FB, $F_{(1,\ 26)} = 6.411$,

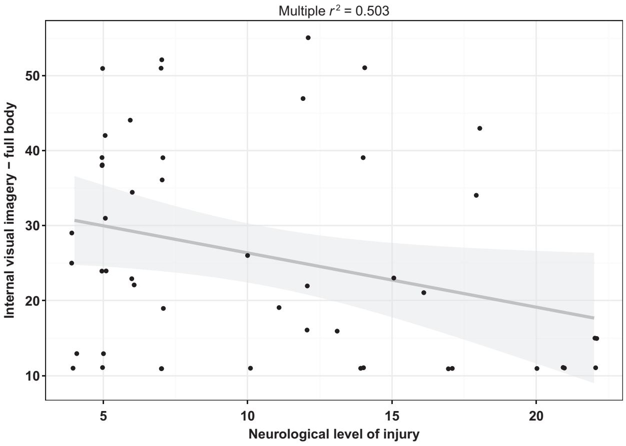

Figure 3. Neurological level of lesion and MI. SCI participants with more caudal NLI show worse 'Internal Visual Imagery' (higher scores in IVI correspond to worse performance). Points represent the individual scores. NLI – C1-C8: 1–8, T1-T12: 9–20, L1-L5: 21–25, S1-S5: 26–30. Multiple r^2 values are reported as index of goodness of fit of the model (from 0 to 1, that stands for perfect fit).

$p = .018$, $\eta^2 = .20$. By separately analysing EVI-FB data from participants with ($n = 20$) and without ($n = 29$) musculoskeletal pain, linear models did not reach statistical significance (ps $\geq .15$) and effect sizes were small ($.02 \leq \eta^2 \leq .10$). Nevertheless, as shown in Figure 4, the EVI-FB imagery was more difficult with longer time since injury for the patients with muscular pain, while for the patients without muscular pain it showed to be easier with longer time since injury.

Musculoskeletal pain was correlated with a decline in KIN-FB imagery over time, $F_{(1,\ 18)} = 14.971, p = .001, \eta^2 = .45$ (Figure 5).

Head and shoulder motor imagery

The lesion completeness only significantly impacted the scores relating to HS actions (IVI-HS: $F_{(1,\ 26)} = 7.343, p = .012, \eta^2 = .22$; EVI-HS:$\mathrm{F}_{(1,\ 26)} = 6.365, p = .018, \eta^2 = .20$; KIN-HS: $F_{(1,\ 26)} = 6.778, p = .015, \eta^2 = .21$). In all these cases, patients with complete lesions ($n = 24$) had less vivid imagery (IVI-HS: 9.38 ± 4.86; EVI-HS: 9.83 ± 5.94; KIN-HS: 9.25 ± 4.77) than those with incomplete lesions ($n = 25$) (IVI-HS: 6.30 ± 0.74; EVI-HS: 6.44 ± 1.16; KIN-HS: 6.28 ± .74).

Statistical analyses on IVI, EVI, and KIN subscales are summarized in Table 3.

Finally, in all cases, clinical aspects did not influence UL scores. No statistically significant correlation between SCIM-III or Extraversion subscale and the motor imagery subscales was found (all ps > .12, Spearman's correlations Bonferroni corrected).

Discussion

In this study, the presence of MI deficits after SCI was investigated with a particular focus on the potential effects of the subjects' clinical variables and personality traits. The main result shows a somato-topographic distribution of MI deficits that specifically involves

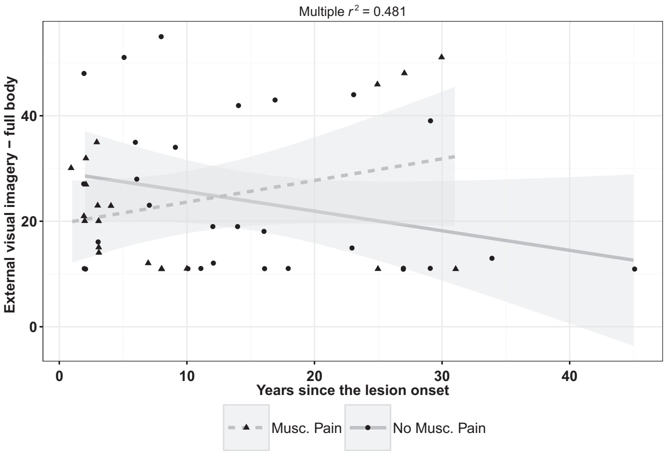

Figure 4. Pain and EVI. Regressions on VMIQ-2 scores relating to 'External Visual Imagery' for full-body actions show an opposite pattern over time, due to the presence or absence of musculoskeletal pain. Points represent the individual score. Multiple r^2 values are reported as index of goodness of fit of the model (from 0 to 1, that stands for perfect fit).

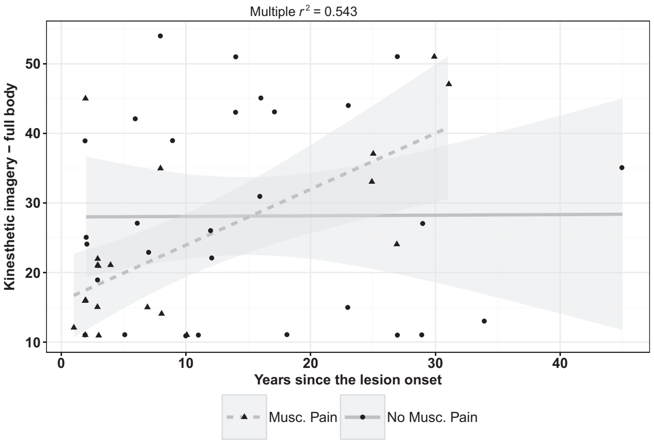

Figure 5. Pain and KIN. Regressions on VMIQ-2 scores relating to 'Kinaesthetic Imagery' for full-body actions show a flat trend over time, due to the presence or absence of musculoskeletal pain. Points represent the individual score. Multiple r^2 values are reported as index of goodness of fit of the model (from 0 to 1, that stands for perfect fit).

full-body actions (that are impossible to perform) but spares the actions relating to upper body parts. Lesion level and completeness, time interval from lesion onset, and pain do influence MI. In contrast, no effects due to autonomy in daily life activities and personality traits were found.

Topographic deficits of MI in SCI

Previous evidence concerning MI after SCI has indicated a dichotomy between behavioural results and neuro-functional data. In fact, behavioural experiments failed to find any connections between motor deficits and MI (Hotz-Boendermaker *et al.*, 2008), hinting at the possible absence of links between alterations in efferent and afferent information and MI (Hotz-Boendermaker *et al.*, 2008). However, this result contrasts with neuro-functional data, indicating that MI in SCI still engages the central movement networks. In fact, when asked to imagine moving their paralysed feet, paraplegic patients strongly activate brain areas corresponding to both the action execution and action imagery network in healthy subjects (Alkadhi *et al.*, 2005). This seeming discrepancy may be explained by hypothesizing that people after SCI (Fiori *et al.*, 2014) use non-standard MI strategies, possibly recruiting additional memory and attention systems. We found some evidence of this when we analysed the interviews we carried out, as some patients reported, for example, 'Yes, I *remember* this very well', 'I *can see* when I did this action', or 'Sometimes, I try *to recall* how I ran'. The increased activation found in SCI subjects during MI tasks in prefrontal and parietal areas and the additional recruitment of thalamus, putamen/pallidum, and cerebellum (Alkadhi *et al.*, 2005; Hotz-Boendermaker *et al.*, 2008) which are all involved in motor learning and memory also support this hypothesis.

Our data also indicate that, when asked about their subjective, aware experience of MI, SCI subjects show a reduction in MI with respect to healthy controls in terms of score at the MI questionnaire. Crucially, however, the difference between SCI subjects and controls does not appear in the third-person perspective condition, but exists exclusively

Table 3. ANCOVAs on VMIQ-2 scores, effects of clinical variables

		IVI-FB				IVI-UL				IVI-HS			
	Df	MeanSq	F value	*p*	η^2	MeanSq	*F* value	*p*	η^2	MeanSq	*F* value	*p*	η^2
NP	1.00	34.53	0.19	0.67	0.01	11.57	2.36	0.14	0.08	5.43	0.35	0.56	0.01
MP	1.00	0.01	0.00	0.99	0.00	0.79	0.16	0.69	0.01	1.78	0.11	0.74	0.00
VP	1.00	269.01	1.46	0.24	0.05	3.14	0.64	0.43	0.02	1.08	0.07	0.80	0.00
Lesion	1.00	56.00	0.30	0.59	0.01	14.13	2.88	0.10	0.10	**114.23**	**7.30**	**0.01**	**0.22**
NLI	1.00	**889.52**	**4.83**	**0.04**	**0.16**	17.07	3.48	0.07	0.12	12.93	0.83	0.37	0.03
Years	1.00	118.48	0.64	0.43	0.02	11.87	2.42	0.13	0.09	15.15	0.97	0.33	0.04
NP × NLI	1.00	2.81	0.01	0.90	0.00	4.97	1.01	0.32	0.04	0.81	0.05	0.82	0.00
NP × Years	1.00	61.24	0.33	0.57	0.01	0.02	0.00	0.95	0.00	12.91	0.83	0.37	0.03
MP × NLI	1.00	0.40	0.00	0.96	0.00	0.82	0.17	0.69	0.01	5.97	0.38	0.54	0.01
MP × Years	1.00	495.97	2.69	0.11	0.09	4.68	0.95	0.34	0.04	3.92	0.25	0.62	0.01
VP × NLI	1.00	155.84	0.85	0.37	0.03	7.66	1.56	0.22	0.06	0.98	0.06	0.81	0.00
VP × Years	1.00	496.04	2.69	0.11	0.09	3.65	0.74	0.40	0.03	6.59	0.42	0.52	0.02
Lesion × NLI	1.00	381.11	2.07	0.16	0.07	0.81	0.17	0.69	0.01	17.05	1.09	0.31	0.04
Lesion × Years	1.00	319.50	1.73	0.20	0.06	4.63	0.94	0.34	0.04	11.11	0.71	0.41	0.03
NP × MP	1.00	120.64	0.66	0.43	0.03	5.18	1.05	0.31	0.04	0.03	0.00	0.97	0.00
NP × VP	1.00	74.79	0.41	0.53	0.01	16.11	3.28	0.08	0.11	0.01	0.00	0.98	0.00
NP × Lesion	1.00	6.22	0.03	0.86	0.00	0.05	0.01	0.92	0.00	0.70	0.04	0.83	0.00
MP × VP	1.00	352.47	1.91	0.18	0.07	0.66	0.14	0.72	0.01	14.85	0.95	0.34	0.04
MP × Lesion	1.00	45.82	0.25	0.62	0.01	0.07	0.01	0.90	0.00	0.40	0.03	0.87	0.00
VP × Lesion	1.00	254.73	1.38	0.25	0.05	0.18	0.04	0.85	0.00	15.79	1.01	0.32	0.04
NP × MP × Lesion	1.00	27.41	0.15	0.70	0.01	1.34	0.27	0.60	0.01	12.80	0.82	0.37	0.03
MP × VP × Lesion	1.00	702.13	3.81	0.06	0.13	0.62	0.12	0.73	0.01	11.22	0.72	0.41	0.03
Residuals	26.00	184.21				4.91				15.64			

Continued

Table 3. *(Continued)*

		EVI-FB				EVI-UL				EVI-HS			
	Df	MeanSq	*F* value	*p*	η^2	MeanSq	*F* value	*p*	η^2	MeanSq	*F* value	*p*	η^2
NP	1.00	2.59	0.01	0.91	0.00	0.68	0.12	0.73	0.01	1.43	0.07	0.80	0.00
MP	1.00	0.71	0.00	0.95	0.00	2.00	0.36	0.56	0.01	12.40	0.59	0.45	0.02
VP	1.00	396.54	2.15	0.15	0.08	0.25	0.04	0.83	0.00	0.09	0.00	0.95	0.00
Lesion	1.00	0.14	0.00	0.98	0.00	16.54	2.96	0.10	0.10	**134.12**	**6.34**	**0.02**	**0.20**
NLI	1.00	653.91	3.55	0.07	0.12	11.79	2.11	0.16	0.07	28.29	1.34	0.26	0.05
Years	1.00	26.36	0.14	0.71	0.01	12.69	2.27	0.14	0.08	0.73	0.04	0.85	0.00
NP × NLI	1.00	6.50	0.04	0.85	0.00	0.10	0.02	0.89	0.00	6.49	0.31	0.58	0.01
NP × Years	1.00	570.43	3.10	0.09	0.11	1.55	0.28	0.60	0.01	6.72	0.32	0.58	0.01
MP × NLI	1.00	136.60	0.74	0.40	0.03	0.51	0.09	0.77	0.00	26.58	1.26	0.27	0.05
MP × Years	1.00	870.34	4.72	0.04	0.15	10.26	1.84	0.19	0.07	49.28	2.33	0.14	0.08
VP × NLI	1.00	5.08	0.03	0.87	0.00	3.47	0.62	0.44	0.02	2.37	0.11	0.74	0.00
VP × Years	1.00	95.51	0.52	0.48	0.02	12.16	2.18	0.15	0.08	3.70	0.17	0.68	0.01
Lesion × NLI	1.00	270.16	1.47	0.24	0.05	1.45	0.26	0.61	0.01	41.90	1.98	0.17	0.07
Lesion × Years	1.00	278.74	1.51	0.23	0.06	3.17	0.57	0.46	0.02	17.54	0.83	0.37	0.03
NP × MP	1.00	105.63	0.57	0.46	0.02	4.31	0.77	0.39	0.03	3.58	0.17	0.68	0.01
NP × VP	1.00	45.15	0.24	0.62	0.01	19.61	3.51	0.07	0.12	0.88	0.04	0.84	0.00
NP × Lesion	1.00	0.05	0.00	0.99	0.00	3.37	0.60	0.44	0.02	0.34	0.02	0.90	0.00
MP × VP	1.00	467.65	2.54	0.12	0.09	1.34	0.24	0.63	0.01	25.76	1.22	0.28	0.04
MP × Lesion	1.00	50.61	0.28	0.60	0.01	0.25	0.04	0.83	0.00	0.26	0.01	0.91	0.00
VP × Lesion	1.00	3.34	0.02	0.89	0.00	7.34	1.31	0.26	0.05	44.57	2.11	0.16	0.07
NP × MP × Lesion	1.00	461.19	2.50	0.13	0.09	16.31	2.92	0.10	0.10	21.61	1.02	0.32	0.04
MP × VP × Lesion	1.00	0.04	0.00	0.99	0.00	5.33	0.95	0.34	0.04	6.10	0.29	0.60	0.01
Residuals	26.00	184.24				5.58				21.14			

Continued

Table 3. *(Continued)*

		KIN-FB				KIN-UL				KIN-HS			
	Df	MeanSq	*F* value	*p*	η^2	MeanSq	*F* value	*p*	η^2	MeanSq	*F* value	*p*	η^2
NP	1.00	33.81	0.21	0.65	0.01	8.82	1.49	0.23	0.05	1.74	0.11	0.75	0.00
MP	1.00	203.40	1.28	0.27	0.05	11.61	1.97	0.17	0.07	0.84	0.05	0.82	0.00
VP	1.00	166.83	1.05	0.32	0.04	2.49	0.42	0.52	0.02	0.27	0.02	0.90	0.00
Lesion	1.00	103.67	0.65	0.43	0.02	18.97	3.21	0.09	0.11	**110.08**	**6.74**	**0.01**	**0.21**
NLI	1.00	275.36	1.73	0.20	0.06	17.25	2.92	0.10	0.10	2.75	0.17	0.69	0.01
Years	1.00	**708.29**	**4.45**	**0.04**	**0.15**	8.52	1.44	0.24	0.05	18.06	1.10	0.30	0.04
NP × NLI	1.00	42.79	0.27	0.61	0.01	2.33	0.39	0.54	0.01	1.14	0.07	0.79	0.00
NP × Years	1.00	60.35	0.38	0.54	0.01	0.48	0.08	0.78	0.00	0.01	0.00	0.98	0.00
MP × NLI	1.00	488.79	3.07	0.09	0.11	4.81	0.81	0.38	0.03	11.40	0.70	0.41	0.03
MP × Years	1.00	**1055.07**	**6.62**	**0.02**	**0.20**	5.08	0.86	0.36	0.03	0.25	0.02	0.90	0.00
VP × NLI	1.00	51.48	0.32	0.57	0.01	9.98	1.69	0.20	0.06	0.79	0.05	0.83	0.00
VP × Years	1.00	31.99	0.20	0.66	0.01	0.85	0.14	0.71	0.01	1.40	0.09	0.77	0.00
Lesion × NLI	1.00	12.45	0.08	0.78	0.00	3.24	0.55	0.47	0.02	5.84	0.36	0.56	0.01
Lesion × Years	1.00	407.62	2.56	0.12	0.09	11.88	2.01	0.17	0.07	19.56	1.20	0.28	0.04
NP × MP	1.00	5.98	0.04	0.85	0.00	0.07	0.01	0.92	0.00	3.15	0.19	0.66	0.01
NP × VP	1.00	65.43	0.41	0.53	0.02	18.87	3.20	0.09	0.11	5.39	0.33	0.57	0.01
NP × Lesion	1.00	95.82	0.60	0.45	0.02	2.09	0.35	0.56	0.01	2.03	0.12	0.73	0.01
MP × VP	1.00	156.78	0.98	0.33	0.04	3.44	0.58	0.45	0.02	1.03	0.06	0.80	0.00
MP × Lesion	1.00	35.07	0.22	0.64	0.01	0.02	0.00	0.96	0.00	3.15	0.19	0.66	0.01
VP × Lesion	1.00	563.08	3.54	0.07	0.12	1.92	0.33	0.57	0.01	7.48	0.46	0.51	0.02
NP × MP × Lesion	1.00	374.88	2.35	0.14	0.08	2.90	0.49	0.49	0.02	4.13	0.25	0.62	0.01
MP × VP × Lesion	1.00	85.18	0.54	0.47	0.02	0.34	0.06	0.81	0.00	18.20	1.11	0.30	0.04
Residuals	26.00	159.29				5.90				16.34			

ANCOVAs table for each VMIQ-2 subscale. Not all the interactions were considered because clinical aspects were not equally distributed among cells. This table is organized in 3 'subtables'. At the top, the IVI subscales tables (IVI-FB, IVI-UL, and IVI-HS). In the middle, the EVI subscales tables (EVI-FB, EVI-UL, and EVI-HS). At the bottom, the KIN subscales tables (KIN-FB, KIN-UL, and KIN-HS). In each subtable, the first two columns represent the name of the effect or interaction, and the degrees of freedom (Df). Then, for each subscale, mean squares (Mean Sq), *F* value, *p* value, and effect size (η^2) are reported. Significant effects or interactions are shown in bold. NP = neuropathic pain, VP = visceral pain, MP = musculoskeletal pain, lesion = completeness of the lesion, years = years since the lesion onset, NLI = neurological level of injury.

in the first-person perspective condition. This confirms that poor performance does not reflect a generic reduction in mental imagery, but rather a possible SCI disorder affecting body and actions imagery. Moreover, the differences in MI relating to different body parts indicate that both paraplegic and tetraplegic participants performed worse for actions involving the full-body imagery as compared to upper body parts imagery, with a significant effect of the level of lesion, in particular for IVI. Thus, MI disorders in SCI seem to be topographically consistent with the localization of sensorimotor deficits. This novel result indicates that deafferentation and deefferentation play a specific role in MI and supports the notion of an inherent link between action imagination and action execution. Interestingly, the possibility that plastic rearrangements of body representations may follow topographic rules has also been suggested in studies describing how synchronous tactile stimulation of the face and fake hand induces the rubber hand illusion in SCI (Scandola *et al.*, 2014; Tidoni, Grisoni, Liuzza, & Aglioti, 2014), a result that is compatible with the fact that face and the hand are mapped contiguously in the somatosensory and motor cortices. The finding that paraplegic people exhibit deficits in the visual discrimination of static and dynamic lower limbs is also in accordance with the hypothesis that topographic remapping may occur across sensory modalities and body parts (Pernigo *et al.*, 2012). Significantly, the lower limb deficit involved both body form and action hinting at a pervasive influence of ongoing body signals on the brain network dedicated to visual body processing (Pernigo *et al.*, 2012). Similarly, impairments in locomotion have been found to affect the capacity to visually perceive point-light displays of human locomotion (Arrighi, Cartocci, & Burr, 2011). Finally, topographic effects were found in a task involving perceptual judgments. In this task, SCI participants observed a series of videos with movement of hands. After the vision, participants had to report via keyboard the shortest time in which they and a young adult could accurately perform these movements. The SCI responses were consistent with their actual performance, with worse judgments in participants with cervical lesions as compared to those with below cervical SCI (Manson *et al.*, 2014).

To sum up, convergent evidence indicates that the brain networks involved in body-related perception and higher-order cognitive processing of body-related information, such as action recognition, peripersonal space perception (Canzoneri, Marzolla, Amoresano, Verni, & Serino, 2013; Serino, Bassolino, Farnè, & Làdavas, 2007), and motor imagery depend on a continuous, bidirectional flow of information between the brain and the body, and in particular on the integration of motor commands and somatosensory feedback.

Influence of clinical variables on MI deficits in SCI

Although in self-reported interviews the variability resulting from personality traits and mood might be important, we can exclude these factors in terms of any influence they may have on our main results. In particular, we did not find any SCI versus control differences for suggestibility and absorption (Tellegen Scale) or for the individual disposition to accept changes in one's own body form and surface (BodyTAP). In addition, there were no correlations between the scores in these scales and MI performance.

As for the lesion level, we found that the higher the lesion, the worse the MI performance (particularly the IVI subscale). This result confirms the role of deafferentation and deefferentation in MI.

In addition, the completeness of the lesion influences MI of actions involving the head and shoulders in all three subscales (i.e., patients with complete lesions perform worse than those with incomplete lesions), while no difference was found for FB and UL actions. The significance of this distinction between complete and incomplete lesions is difficult to assess due to the great variety of clinical characteristics especially in incomplete lesions: residual functions below the lesion may range from only sensory input to some motor output. However, the AIS scores (Ditunno *et al.*, 1994) in our participants affected by incomplete tetraplegia and incomplete paraplegia were similar. We therefore consider the two groups comparable.

The effect of the completeness of the lesion on the MI–HS scores is evident particularly in patients with tetraplegia, where complete lesions are associated with worse MI and in fact tetraplegics affected by complete lesion may be the only ones who are unable to move their head and shoulders. In contrast, patients with incomplete lesions become particularly expert at performing daily life activities using the residual activity of muscles innervated by the spinal accessory nerve (XI cranial nerve), the *plexus cervicalis* (C1-C4), and the *plexus brachialis* (C4-C8). Residual potential movements are ‘hyperused’ in these people, a condition that may in some way explain why people with incomplete damage are better at MI than those with complete lesions.

Opposite to our predictions, we did not find any effects of the degree of autonomy in daily life activities to MI performance. We hypothesized that regularly using a body part in everyday activities would be an important factor in terms of maintaining the ability to imagine performing an action with the body part. In contrast, our results suggest that the preservation of afferent/efferent connections between the body parts and the brain is enough to maintain the mental imagery of motor actions.

In fact, in this case, no differences between afferented and deafferented body parts were present.

Another interesting result concerns the effects of pain on MI. As a whole, the frequency of neuropathic pain in our sample is higher than that reported in previous studies (57.14% vs. 40%, Siddall, McClelland, Rutkowski, & Cousins, 2003). In addition, the subjects with paraplegia complained more about pain than the participants with tetraplegia. We found visceral pain (20%) to be less frequent than neuropathic pain, without any differences linked to the lesion level. Finally, SCI subjects did not complain about musculoskeletal pain any more frequently than the controls.

Patients with chronic lesions and pain tend to report in our interview less MI (in particular KIN), while no influence of pain is observable in patients without chronic pain. Similarly, in EVI-MI a general detrimental effect of pain over time was recorded, although this trend is not as accentuated as the decline in KIN-MI. In addition, there is an opposite pattern in patients without chronic pain in EVI-MI. This might suggest that, while in the presence of pain MI decreases over time, and in the absence of pain, people change their MI strategies moving from the first-person towards a third-person perspective.

A reciprocal influence between MI and pain has already been demonstrated (although with different trajectories) in motor imagery tasks based on brain–computer interface (Vuckovic *et al.*, 2015). Paraplegic patients with central neuropathic pain achieved higher accuracy and had stronger event-related desynchronization than subjects with no pain during a MI task related to hand and feet movements, although there were no statistical differences between body parts (Vuckovic *et al.*, 2015). Unfortunately, in this study the MI perspective was not controlled and we cannot rule out that some compensatory strategies were used. In contrast with this apparent improvement, it has been shown that MI can exacerbate pain and induce dysesthesia in patients without pain sensations (Bowering *et al.*, 2013; Gustin *et al.*, 2008). Neuropathic pain is associated with electrophysiological changes (Boord *et al.*, 2008; Jensen *et al.*, 2013) and processes of cortical and subcortical reorganization. This involves the primary somatosensory cortex (Henderson, Gustin, Macey, Wrigley, & Siddall, 2011; Wrigley *et al.*, 2009), as well as the orbitofrontal, dorsolateral prefrontal, and parietal cortices, the *nucleus accumbens* (Gustin, Wrigley, Siddall, & Henderson, 2010), and the thalamus (Gustin *et al.*, 2010).

The widespread nature of these plastic changes may thus explain the contradictory results concerning the effects of pain on MI and at the same time the use of cognitive strategies in order to execute behavioural tasks. Our results indicate that a general reduction in MI is related to pain, while in the absence of pain people spontaneously reduce internal, first-person MI strategies and enhance external, third-person perspective strategies. In order to deal with the maladaptive effects of SCI symptoms, people spontaneously move towards new strategies in order to execute MI tasks, which are differently influenced by some clinical variables (Fiori *et al.*, 2014; Hotz-Boendermaker *et al.*, 2008).

Limitations of the current study

Some possible limitations of this study deserve discussion. For qualitative studies based on questionnaires in healthy subjects, 49 participants may be a relatively small sample. However, SCI is a relatively small patient population and their recruitment is very difficult. In addition, our participants were selected to give homogeneous subsamples (12 with incomplete paraplegia, 12 with complete paraplegia, 12 with complete tetraplegia, and 13 with incomplete tetraplegia). Representativeness of the sample should be strengthened by these selection criteria.

Another limitation is the use of a new, not yet validated, scale to measure pain. This choice was due to the necessity to have an instrument able to assess the three kinds of pain (neuropathic, visceral, and musculoskeletal).

Conclusions

Our clinical investigation shows that MI in SCI is a very complex function possibly underpinned by multiple cognitive systems and influenced by several clinical variables. We observed that MI in IVI and KIN perspectives might be influenced by the subject's actual body motor control abilities, which is somato-topically organized. As IVI and KIN indices are embodied forms of MI (Lorey *et al.*, 2009), we suggest that our results indicate specific, topographic changes incorporeal awareness in SCI patients (Lenggenhager, Pazzaglia, Scivoletto, Molinari, & Aglioti, 2012; Scandola *et al.*, 2014; Tidoni *et al.*, 2014). This is supported by results regarding the effects of pain, also involving corporeal awareness (Schwoebel *et al.*, 2001). All the changes in SCI patients' motor imagery and body perception probably reflect the complex processes of neural cortical and subcortical reorganization following deafferentation and deefferentation (Henderson *et al.*, 2011). Nevertheless, the analysis of these processes needs further investigation with neurophysiological and neuroimaging techniques. Understanding how the body can modify the brain may provide useful information for the design of personalized devices to assist SCI patients. In addition, a better comprehension of how motor imagery links to actual movements of specific body segments may help to improve the BCI tools devices operated through mental imagery and thus device specific programmes of rehabilitation based on the control of artificial physical agents.

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Supporting Information

The following supporting information may be found in the online edition of the article:

Data S1. The VR pain scale and the modified VMIQ-2 scale.

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EDUCATION

2011 – 2016	**PhD in Cognitive Neuroscience** Laboratory of Cognitive Neuroscience School of Life Science Ecole Polytechnique Fédérale de Lausanne Switzerland Thesis title: *Multisensory and sensorimotor origins of the sense of self*
2009 – 2011	**MSc in Cognitive Neuroscience/Research program in Neuropsychology** Faculty of Psychology and Cognitive Neuroscience Maastricht University The Netherlands Thesis title: *Illusory self-touch and bodily self-consciousness: Investigating the role of touch, proprioception, and motor signals*
2005 – 2009	**Diploma in Psychology** (equivalent to MA) Faculty of Arts, University of Ljubljana Slovenia Thesis title: *Role of metacognition in false memory formation*

EMPLOYMENT HISTORY

2011 - 2016	**Research assistant – Doctoral candidate** Laboratory of Cognitive Neuroscience School of Life Science Ecole Polytechnique Fédérale de Lausanne Supervisor: prof. Olaf Blanke
2011 – 2013	**Teaching assistant**: Neuroscience III: Cognitive and behavioural (master course) Physiology Practicum: EEG (bachelor course) School of Life Science Ecole Polytechnique Fédéral de Lausanne Switzerland

2010	**Research assistant** Project “Concept Shifting Test: Effect of Version and Posture” Faculty of Psychology and Cognitive Neuroscience, Maastricht University The Netherlands Supervisor: prof. Martin van Boxtel
2008 – 2009	**Educationist assistant** Children daycare center H. C. Andersen Ljubljana, Slovenia
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RESEARCH INTERESTS

- Neuropsychology
- Multisensory and sensorimotor integration
- Self-referential processing, self-disorders, schizophrenia
- Body perception and pathology
- Neuroscience of creativity & mindfulness

SCHOLARSHIPS & AWARDS

2009 - 2011	AD Futura Scholarship Slovene human resources development and scholarship fund
2010 – 2011	Huygens Scholarship Programme Nuffic - Netherlands organization for international cooperation in higher education
2010	Top 3% award Maastricht University
2015	Award for the best poster in psychology 19th Annual meeting of Association for the Scientific Study of Consciousness (ASSC) Paris, France

SKILLS

Languages	Fluent in Slovenian and English, proficient in French and Serbo-Croatian, basic German
Software	Office suit, SPSS, Matlab, ExpyVR, E-prime, Brain voyageur, Adobe Illustrator & Photoshop

EXTRACURRICULAR INTERESTS & ACTIVITIES

Visual arts	Passionate about drawing, painting, illustration, screen printing, graphic design, animation • Member of L’Acade: Academie de dessin (2013-2015) • Exhibited paintings at CreaPoly 2013 and 2015
Sports	Swimming • Snowboarding • Windsurfing • Running
Filmmaking	Coup de Coeur prize at Féstival Fecule, Haut et Court 2015 for a short movie entitled “Handmade”

PEER-REVIEWED PUBLICATIONS

Scandola, M., Aglioti, S., Pozeg, P., Avesani, R. & Moro, V. (2016). Motor imagery in spinal cord injured people is modulated by somato-topic coding, perspective taking and post-lesional chronic pain. *Journal of Neuropsychology*, e-pub ahead of print.

Pozeg, P., Galli, G., & Blanke, O. (2015). Those are Your Legs: The Effect of Visuo-Spatial Viewpoint on Visuo-Tactile Integration and Body Ownership. *Frontiers in Psychology*, *6*.

Hara, M., Pozeg, P., Rognini, G., Higuchi, T., Fukuhara, K., Yamamoto, A., Blanke, O., & Salomon, R. (2015). Voluntary self-touch increases body ownership. *Frontiers in Psychology*, *6*.

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Pozeg, P., Paluel, E., Ronchi, R., Solca, M., Al Khodairy, A., Kassouha, A., Jordan, X., & Blanke, O. Body ownership in paraplegia: Implications for pain management and neurorehabilitation (*in preparation*).

Pozeg, P., Serino, A., Rognini, G., & Blanke, O. Sensorimotor manipulation of thought agency and thought insertion in healthy subjects (*in preparation*).

CONFERENCE PRESENTATIONS

Pozeg, P., Rognini, G., Serino, A., Salomon, R., Bleuler, H. & Blanke, O. (2015, July). Neurological and Robot-Controlled Induction of Apparition. Poster presented at 19th Annual meeting of Association for the Scientific Study of Consciousness (ASSC), Paris, France.

Pozeg, P., Rognini, G., Serino, A., Salomon, R., Bleuler, H. & Blanke, O. (2015, June). Neurological and Robot-Controlled Induction of Apparition. Poster presented at AEGINA Summer school on “The social self: how social interactions shape body and self-representations”, Aegina, Greece.

Rognini, G., Pozeg, P., Serino, A., Bleuler, H. & Blanke, O. (2015, June). Ghost experience induced by robotic sensorimotor conflicts. Poster presented at 16th International Multisensory Research Forum, Pisa, Italy.

Pozeg, P. (2014, October). Those are your legs: The effect of visuo-spatial perspective on the visuo-tactile interactions and body ownership. Oral presentation at 2nd VERE PhD Symposium, Barcelona, Spain.

Pozeg, P., Galli, G. & Blanke, O. (2014, June). Those are your legs: The effect of visuo-spatial perspective on the visuo-tactile interactions and body ownership. Poster presented at 15th International Multisensory Research Forum, Amsterdam, The Netherlands

Pozeg, P., Rognini, G. & Blanke, O. (2013, September). Moving my hand forward to touch my back. Poster presented at Lemanic Neuroscience Annual Meeting. Les Diablerets, Switzerland.

Pozeg, P., Rognini, G. & Blanke, O. (2013, June). Moving my hand forward to touch my back. Poster presented at 14th International Multisensory Research Forum, Jerusalem, Israel.

Pozeg, P. (2011, October). Crossing the hands increases illusory self-touch. Oral presentation at 1st VERE PhD Symposium, Barcelona, Spain.