Abstract

Recently, a monothematic delusion of body ownership due to brain damage (i.e., the embodiment of someone else's body part within the patient's sensorimotor system) has been extensively investigated. Here we aimed at defining in-depth the clinical features and the neural correlates of the delusion. Ninety-six stroke patients in a sub-acute or chronic phase of the illness were assessed with a full ad-hoc protocol to evaluate the embodiment of an alien arm under different conditions. A sub-group of seventy-five hemiplegic patients was also evaluated for the embodiment of the movements of the alien arm. Fifty-five patients were studied to identify the neural bases of the delusion by means of voxel-based lesion-symptom mapping approach. Our results show that, in forty percent of the whole sample, simply viewing the alien arm triggered the delusion, but only if it was a real human arm and that was seen from a 1st-person perspective in an anatomically-correct position. In the hemiplegic sub-group, the presence of the embodiment of the alien arm was always accompanied by the embodiment of its passive and active movements. Furthermore, the delusion was significantly associated to primary proprioceptive deficits and to damages of the corona radiata and the superior longitudinal fasciculus. To conclude, we show that the pathological embodiment of an alien arm is well-characterized by recurrent and specific features and might be explained as a disconnection deficit, mainly involving white matter tracts. The proposed exhaustive protocol can be successfully employed to assess stroke-induced disorders of body awareness, unveiling even their more undetectable or covert clinical forms.

Key words: body ownership, bodily self, brain-damaged patients, delusional body ownership, sense of agency

1. Introduction

The sense of body ownership is defined as the conscious experience of the body as one's own (Gallagher, 2000) and can be dramatically and selectively altered in stroke populations (Martinaud, Besharati, Jenkinson, & Fotopoulou, 2017; Vallar & Ronchi, 2009; Zeller, Gross, Bartsch, Johansen-Berg, & Classen, 2011). A prototypical disorder of body ownership, first reported by Gerstmann (Gerstmann, 1942) is known as somatoparaphrenia (Gandola et al., 2012; Romano & Maravita, 2019; Vallar & Ronchi, 2009). In this condition, often associated to contralesional left neglect (Halligan, Fink, Marshall, & Vallar, 2003) and/or anosognosia for hemiplegia (Karnath, Baier, & Nagele, 2005; Orfei et al., 2007; Piedimonte et al., 2015), patients maintain various delusional beliefs regarding the ownership of their paralyzed limbs. In the most classic presentation, the ownership of the own limb is ascribed to another person as, for instance, the doctor or a relative. Recently, the reverse of this classic somatoparaphrenic delusion, namely the belief that someone else’s limb belongs to oneself has been extensively investigated (Berti, Garbarini, & Pia, 2015; Fossataro et al., 2020; Fossataro, Bruno, Gindri, Pia, et al., 2018; Fossataro, Gindri, Mezzanato, Pia, & Garbarini, 2016; Garbarini et al., 2014; Garbarini et al., 2015; Garbarini & Pia, 2013; Garbarini, Pia, Fossataro, & Berti, 2017; Garbarini et al., 2013; Pia, Garbarini, Fossataro, Burin, & Berti, 2016; Pia, Garbarini, Fossataro, Fornia, & Berti, 2013; Ronga et al., 2018). In details, whenever someone else’s arm is located on a table in a body-congruent perspective, these patients (E+) treat and care for that hand as their own. Interestingly, Gerstmann (Gerstmann, 1942) reported a patient experiencing a delusion of owning someone else’s’ arm but only if this person was located in close proximity. Similarly, Preston and Newport (Preston & Newport, 2008) described a patient that sometimes spontaneously reported a sense of embodiment of another person’s arm. The delusion we study here is not a mere verbal confabulation, but instead, it reflects a real embodiment of the alien arm within the patient’s sensorimotor system. Firstly, somatosensory stimuli delivered to the alien hand elicit a comparable phenomenological/physiological responses as those delivered to the own healthy hand (Fossataro et al., 2020; Garbarini et al., 2014; Pia et al., 2013). Secondly, the alien hand movements modulate the motor parameters of the patient's intact arm movements (Garbarini et al., 2013) and the representation of the patient's personal/peripersonal space (Fossataro et al., 2016; Garbarini et al., 2015; Ronga et al., 2018) as if the moving alien arm were the patients' real arm.

The literature on the delusion investigated quite small samples of patients, without providing a full clinical picture. Moreover, with respect to its neural correlates, some of those studies employed only descriptive overlay lesion plot techniques (Fossataro et al., 2020; Fossataro, Bruno, Gindri, Pia, et al., 2018; Garbarini et al., 2014; Garbarini et al., 2015; Garbarini et al., 2013), which were not sufficient to obtain solid anatomical evidence trough the lesion subtraction approach. Here we present the first exhaustive anatomo-clinical picture of the delusion in a large group of patients (i.e., all the patients tested so far by our group). We examined in-depth the clinical prevalence of the pathological embodiment in different groups of brain-damaged patients, as well as its association with other concomitant deficits. Moreover, we presented all the conditions under which the pathological embodiment of an alien arm and an alien arm's movement occur using the full version of an ad-hoc protocol, some parts of which have been employed in previous studies (Fossataro, Bruno, Gindri, Pia, et al., 2018; Fossataro et al., 2016; Garbarini et al., 2014; Garbarini et al., 2015; Garbarini & Pia, 2013; Garbarini et al., 2013; Pia et al., 2013). Furthermore, we delineated the delusion by means of lesion subtraction technique, which is a very useful approach to distinguish between structures that are simply often damaged from structures that are specifically required for the function of interest (Rorden, Karnath, & Bonilha, 2007).

2. Methods

Here we report how we determined our sample size, all data exclusions (if any), all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study

2.1. Participants

Participants were selected from a series of stroke patients admitted to four different rehabilitation centers from 2010 to 2017 and were included in previous published papers on the delusion of ownership (Fossataro et al., 2020; Fossataro, Bruno, Gindri, Pia, et al., 2018; Fossataro et al., 2016; Garbarini et al., 2014; Garbarini et al., 2015; Garbarini & Pia, 2013; Garbarini et al., 2013; Pia et al., 2013). The inclusion criteria were the presence of a documented unilateral brain damage and contralesional upper limb motor and/or sensory deficits demonstrated by a neurological exam (see description below and scores in table 1). On the other hand, the exclusion criteria were any previous neurological diseases written in the medical records, any kind of language/cognitive impairments objectively precluding the ability to understand the instructions for the embodiment evaluation (see below), and the presence of such a severe form of neglect to prevent the perception of the stimuli delivered during the embodiment evaluation (see below). Accordingly, ninety-six patients (forty-three females and fifty-three males, age range 37-86 years, educational level range 5-18 years; illness onset range 20-200 days), seventy-nine with right-brain damage (hereinafter RBD) and seventeen with left-brain damage (hereinafter LBD) gave their written informed consent to enter the study (see table 1 for more demographical and clinical data). The study was approved by the ethical committee of the University of Turin (Project "Conscious brain: neural basis of motor and body awareness" protocol 1/2014/B1). No part of the study procedures and analysis were pre-registered prior to the research being conducted. Raw data of the behavioral analysis can be found at the urlhttps://osf.io/r4sfp. On the contrary, the conditions of our ethics approval do not permit public archiving of anonymized CT/MRI scans. Readers seeking access to the data should contact the corresponding author LP at the Department of Psychology, University of Turin. Access can be granted only to named individuals in accordance with ethical procedures governing the reuse of sensitive clinical data. There are no further conditions for granting access on request.

Patients were screened with either the Italian version of the Mini Mental State Examination (Measso et al., 1993) or the Montreal Cognitive Assessment (Nasreddine, Phillips, & Chertkow,

2012) in order to evaluate the overall cognitive impairment. Handedness was assessed with the Edinburg inventory (Oldfield, 1971). Contralesional motor and tactile deficits were assessed according to a standardized protocol (Bisiach & Faglioni, 1974), whereas proprioception was assessed by means of the joint position matching task in which the patient is asked to recreate a joint angle in the absence of vision (Fossataro, Bruno, Gindri, & Garbarini, 2018; Goble, 2010). Unawareness for tactile (Pia, Cavallo, & Garbarini, 2014; Pia, Garbarini, Burin, Fossataro, & Berti, 2015) and motor deficits was assed according to a previously published procedure (Pia, Spinazzola, et al., 2014; Spinazzola, Bellan, Pia, & Berti, 2014). The presence of left extrapersonal neglect was assessed with the Behavioral Inattention Test (Wilson, Cockburn, & Halligan, 1987), whereas left personal neglect with the Bisiach et al. methodology (Bisiach, Vallar, Perani, Papagno, & Berti, 1986). Patients were also evaluated for somatoparaphrenia (Fotopoulou et al., 2011) and verbal asomatognosia (Feinberg, Haber, & Leeds, 1990).

- Table 1 about here -

2.2. Embodiment of an external object

All ninety-six patients were administered this part of the assessment in which we manipulated the number of available objects, as well as the congruency in terms of posture or body-like appearance. Specifically, the patient's arm(s) and/or the co-experimenter s arm or a neutral object were present on the table in different positions with colored cubes in front of them. Patients had to identify their own hands by answering the question: *"What is the color of the cube that is currently in front of your left (right) hand?"; Quale è il colore del cubo che in questo momento è di fronte alla sua mano sinistra (o destra)?"*.

The procedure took place in a quiet hospital room. The experimenter, the patient, and a same-gender co-experimenter, who actively participated to the assessment, were present. The patient sat on a wheelchair at a 150 cm x 70 cm x 80 cm table, while, according to the different conditions, the co-experimenter sat on a chair either on the opposite side of the table or behind the patient. A white barber sheet covered the patient's trunk and arms, leaving visible the table surface. Here we manipulated the number of available objects, as well as their congruency in terms of posture or body-like appearance. As a result, three sets of conditions were administered. The first set involved both of the patient's arms (see figure 1A, labeled Patient's Arms PAs). The second set included one of the patient's arms and one external object (i.e., either one co-experimenter's arm or one wooden cooking spoon; see figure 1B, labeled Patient's Arm & External Object PA_EO). The third set involved both of the patient's arms and one external object (i.e., either one co-experimenter's arm or one wooden cooking spoon; see figure 1C, labeled Patient's Arms & External Object PAs_EO). Additionally, in a subset of fourteen randomly selected patients, we added another condition in which the external object was a rubber hand.

According to each set of conditions (see the description below), the experimenter placed the stimuli (i.e., patient's arms, the co-experimenter's arm, and the wooden cooking spoon) visible on the table, palms facing down. At the beginning of each condition, patients were preliminarily asked (three times) to verbally report the number of arms on the table (i.e., one, two or three) and to name the color of three 5cm x 5cm wooden cubes (blue, green and red). In order to participate in the experiment, a patient had to be errorless in counting the arms and in naming the color of the cubes (i.e., if neglect prevented the perception of these stimuli, patients were not included in the study). Then, the experimenter placed one cube in front of each hand present on the table (at a distance of approximately 5 cm) and asked the patient *"What is the color of the cube that is currently in front of your left (right) hand"*. Then, the experimenter changed the cube positions and started another trial. These trials were administered eight times within each condition and the percentage of times the patient reported the block in front of each hand (or the spoon) was recorded.

The set of conditions PAs (see figure 1A) were administered to obtain a baseline measure of the patient's body ownership. Indeed, patients left and right arms were placed on the table perpendicular to the patient's shoulder, at a distance of 25 cm from the midline (figure 1A, condition 1). The total number of trials was 16 (8 "*What is the color of the cube that is currently in front of your left (right) hand?*" questions x 2 hands). Questions for each hand were randomized within subjects.

The set of conditions PA_EO (see figure 1B) wase administered to investigate whether and how postural and body-like appearance congruencies of the external object affected patient's body ownership. For the postural congruency, the co-experimenter's left (figure 1B, condition 2) or right (figure 1B, condition 3) arm was placed in a 1st person perspective perpendicular with respect to the corresponding patient's shoulder (at a distance of 25 cm from the patient's body midline). For right-brain damaged patients, the co-experimenter's *left* arm was also placed in a 3rd person perspective (figure 1B, condition 4 upper part), whereas for left-brain damaged patients the co-experimenter's right arm was also placed in a 3rd person perspective (figure 1B, condition 4 lower part). The total number of trials was 48 (8 "*What is the color of the cube that is currently in front of your left (right) hand?*" questions x 2 hands x 3 levels). Questions for each hand were randomized within subjects. As regards the body-like appearance, a wooden cooking spoon was placed in a 1st person perspective perpendicular with respect to the patient's corresponding shoulder (figure 1B, condition 5). The total number of trials for the two conditions in which the identity of the external object was manipulated was 16 (8 "*What is the color of the cube that is currently in front of your left (right) hand?*" questions x 2 hands). Questions for each hand were randomized within subjects. The order of the four conditions was randomized between subjects.

The set of conditions PAs_EO were administered to investigate again the role of postural and body-like appearance congruencies of the external object on patient's body ownership but here both patient's arms were present on the table (see figure 1C). As regards the postural congruency, the co-experimenter's left (figure 1C, condition 6) or right (figure 1C, condition 7) arm could be placed in a 1st person perspective perpendicular with respect to the corresponding patient's shoulder (at a distance of 25 cm from the patient's midline). Consequently, the patient's arm was misaligned with respect to the patient's shoulder (at a distance of 35 cm from the midline). For right-brain damaged patients, the left co-experimenter's arm could also be misaligned (figure 1C, condition 8 upper part) with respect to the patient's left shoulder (35 cm from the patient's midline), whereas the patient's left arm was aligned (25 cm between the patient's left hand and the patient's midline). The co-experimenter's left arm was also placed in a 3rd person perspective (figure 1C, condition 9 upper part). For left-brain damaged patients, the right co-experimenter's arm could be also misaligned (figure 1C, condition 8 lower part) with respect to the patient's right shoulder (35 cm from the patient's midline), whereas the patient's right arm was aligned (25 cm between the patient's right hand and the patient's midline). The co-experimenter's right arm was also placed in a 3rd person perspective (figure 1C, condition 9 lower part). The total number of trials was 64 (8 "*What is the color of the cube that is currently in front of your left (right) hand?*" questions x 2 hands x 4 conditions). Questions for each hand were randomized within subjects. As regards the body-like appearance, a wooden cooking spoon was placed in a 1st person perspective perpendicular with respect to the corresponding patient's shoulder (figure 1C, condition 10). The total number of trials was 16 (8 "*What is the color of the cube that is currently in front of your left (right) hand?*" questions x 2 hands). Questions for each hand were randomized within subjects. The order of the five conditions was randomized between subjects. The order of the three sets of conditions was randomized between subjects. In a subset of fourteen randomly selected E+ patients, the object could be also a rubber hand. This additional set of conditions was administered to examine if the realism of the alien hand (i.e., a real hand vs. a human-like fake hand) played a role in order for the delusion to occur.

- Figure 1 about here -

2.3. Embodiment of the alien arm movement

A subset of seventy-five patients (sixty-three RBD and twelve LBD patients), with the additional prerequisite of having severe contralesional motor deficits to both proximal and distal parts of the body were administered this part of the assessment in which we manipulated the voluntariness and the authorship of a reaching movement according to two different sets of conditions. Specifically, both the patient's arms and one co-experimenter's arm were present on the table in different positions and different colored cubes were placed vertically aligned with respect to the patient's midline at a reaching distance. The patient's and/or the co-experimenter's arm had to passively/actively reach the colored cubes or to stay still in different conditions. Patients had to identify their own reaching movements by answering the question: "*Did your own left (or right) hand reach the cube?; La sua mano sinistra (o destra) ha raggiunto il cubo?"*.

The procedure was the same as for the embodiment of the external object and the assessment always involved three arms, the patient's arms and one co-experimenter's arm (see figure 1C). The spatial positions varied as in conditions 6-9 of the embodiment of the external object assessment. Specifically, for RBD patients, the co-experimenter's left arm was aligned (figure 2, condition 1, 3, 5 and 7) or misaligned (figure 2, condition 2, 4, 6 and 8) with respect to the patient's shoulder. The same happened for LBD patients, namely the co-experimenter's right arm was aligned (figure 2, condition 1, 3, 5 and 7) or misaligned (figure 2, condition 2, 4, 6 and 8) with respect to the patient's shoulder. Here we manipulated the voluntariness and the authorship of a reaching movement according to two different sets of conditions. The first involved passive reaching movements (see figure 2A, labeled Passive Movements PM), the second active reaching movements (figure 2B, labeled Active Movements AM).

As for the embodiment of the external object assessment, the arms (three) were placed palms facing down on the table in the given position. At the beginning of each condition, patients were preliminarily asked (three times) to verbally report the number of arms on the table (i.e., three) and to name the color of the three cubes. In order to participate in the experiment, a patient had to be errorless in counting the arms and in naming the color of the cubes. Then, the experimenter placed two of the three cubes vertically aligned with respect to the patient's midline at a reaching distance. The first cube was placed approximately 40 cm from the patient's body, whereas the second around 50 cm. Then, the experimenter instructed the patient with the specific rules of that condition (see below). After each trial, the experimenter asked the patient *"Did your own left (or right) hand reach the cube?.* Within each condition, the question was asked eight times for each hand and the percentage of "yes/no" answers for each hand was recorded. Then, the experimenter changed the cube positions and started another condition (See figure 1B for a picture of each condition).

The set of PM conditions was administered to investigate whether or not the authorship of passive reaching movement affected the patient's embodiment of the alien arm movement (see figure 2A). Indeed, the examiner passively moved the patient's arm (figure 2AA, condition 1 and 2) or the co-experimenter arm (figure 2A, condition 3 and 4) to reach the red/green/blue cube. The total number of trials was 32 (8 *"Did your own left (or right) hand reach the cube"* x 4 conditions). The moved hand was randomized within subjects. The order of the two conditions was randomized between subjects.

The set of AM conditions was administered to examine if the authorship of an active reaching movement affected patient's embodiment of the alien arm movement (see figure 2B). The experimenter asked the patient to reach the red/green/blue cube with his/her left/right arm but in some conditions, the co-experimenter stayed still (figure 2B, condition 5 and 6) whereas in others (figure 2B, condition 7 and 8) he/she reached the cube. The total number of trials was 32 (8 *"Did your own left (or right) hand reach the cube"* x 4 conditions). The moving hand was randomized within subjects. The order of the two conditions was randomized between subjects. The three sets of conditions of the embodiment of alien arm movements were randomized between subjects. The embodiment of the external object and the embodiment of the alien arm movements assessment were randomized between subjects.

- Figure 2 about here -

2.4. Lesion comparison

In fifty-five stroke patients, for whom CT or MR scans of a focal and circumscribed right or left infarction were available, an analysis of the lesional pattern was performed. In those patients for whom the digital images were available (n =13), lesions were manually delineated on axial slices of the individual scans employing MRIcron (Rorden et al., 2007), and then normalized with the Clinical Toolbox included in SPM8 (Rorden, Bonilha, Fridriksson, Bender, & Karnath, 2012). MR scans were co-registered with a high-resolution T1-weighted structural scan in the normalization process. For the rest of the patients (n = 42) admitted before digital formats became available to us, lesions were drawn manually with MRIcron (Rorden et al., 2007) onto a normalized T1-weighted template MRI from the Montreal Neurological Institute using the identical or closest matching transversal slice of each individual. This procedure was achieved by an expert operator (L.P.) and double-checked by two other raters (D.B. and C.F.). In the six cases of disagreement, an intersection lesion map was used. It is worth noticing that combining lesions mapped onto both individual scans and standard templates has already been employed (Sperber & Karnath, 2016). The conditions of our ethics approval do not permit public archiving of anonymized CT/MRI scans. Readers seeking access to the data should contact the corresponding author RR at the Department of Psychology, University of Turin. Access can be granted only to named individuals in accordance with ethical procedures governing the reuse of sensitive clinical data.

3. Results

3.1. Embodiment of an external object

In order to detect clinical subgroups on the basis of similar behavioral patterns, we used the s Statistica 10 software (Statsoft, USA) to run agglomerative hierarchical cluster analyses (Newcomer, Steiner, & Bayliss, 2011) without a priori specification and with the squared Euclidean distance as the proximity measure and the Ward's minimum variance criterion as the agglomerative method. This analysis was performed along all conditions separately for right and left-brain damaged patients on the percentage of times the patient reported the block in front of each hand,or the spoon(i.e., answer to the question "*What is the color of the cube that is currently in front of your left (right) hand?")*. In the PAs set of conditions, both the arms of the patient were present (see figure 1A). In the set of conditions PA_EO, we manipulated the postural and body-like appearance congruencies of the external object (see figure 1B). In the PAs_EO set of conditions, we manipulated again postural or body-like appearance congruencies of the external object but both patient's arms were present on the table (see figure 1C). Between-groups statistical comparisons along conditions and neurological/neuropsychological features were performed by means of Mann-Whitney U Tests, t-test or t-test on percentages on the number of patients with available data for each specific measure.

In the preliminary phase, all patients were 100% correct to report the number of arms on the table as well as to name the color of three wooden cubes. With respect to the seventy-nine RBD patients, the analysis yielded two groups, one of thirty-four E+ patients and the other of forty-five E- patients. The same analysis on seventeen LBD patients yielded two groups, one of five E+ patients and the other of twelve E- patients (see table 1).

Statistical analyses along conditions (see below) showed in each group, and in each condition that the mean percentage of answers to the question "*What is the color of the cube that is currently in front of your left (right) hand?"* were always either > 95% (i.e., the patients reported more than 95% of times the color in front of that hand, or spoon) or < 5% (i.e., the patients reported less than 5% of times the color in front of that hand). For this reason, those results were graphically represented in categorical terms (i.e., ✓ = > 95% and **X** < 5%) rather than in percentage. In the PAs set of conditions (see figure 1A), no significant change in the percentage of times the block in front of each hand was reported either between- or within groups was found, being all nearby 100% in both RBD and LBD (see figure 3A). These data indicate that when only the patient's arms were present, both ipsilesional and contralesional arms were correctly attributed to the own body by all patients.

In the PA_EO set of conditions (see figure 1B), in RBD patients the percentage of times the cube in front of the co-experimenter's hand was reported was significantly ($p<.0001$) higher in E+ (mean= 98.9, SD= 4.74) than in E- group (mean= .28, SD= 1.86) in condition 2 only. In LBD patients, the percentage of times the cube in front of the co-experimenter's hand of each hand was reported was significantly ($p<.001$) higher in E+ (mean= 97.5, SD= 5.6) than in E- group (mean= 1.04, SD= 3.61) in condition 3 only (see figure 3B). These data show that in E+ patients, if the co-experimenter's correspondent arms were present, the pathological embodiment emerged if the arm was presented from a 1st person perspective in an anatomically-correct position.

In the PAs_EO set of conditions (see figure 1C), in RBD patients, the percentage of times that cube in front of the co-experimenter's hand was reported was significantly ($p< .0001$) higher in E+ group (mean= 99.44, SD= 4.74) with respect to E- group (mean= 0.28, SD= 1.86) in condition 6 only. As regards left-brain damaged patients, the percentage of times that the cube in front of the co-experimenter's hand was reported was significantly ($p< .001$) higher in E+ (mean= 97.5, SD= 5.6) with respect to E- (mean= 1.04, SD= .86) group in condition 7 only (see figure 3Ct). It is worth noting that in the subgroup of fourteen E+ patients in which the object could be also a rubber hand, they showed the same pattern as in condition 10, namely the one with a wooden cooking spoon. These data show that in E+ patients if both the patient's and the co-experimenter's correspondent arms are present, the pathological embodiment emerges if the co-experimenter's arm is presented from a 1st person perspective in anatomically-correct position, internally to the patients' real arm, and parallel to it.

As regards the neurological/neuropsychological features, E+ and E- groups did not differ (Mann-Whitney U Tests, t-test) in terms of age (E+: mean = 69.18, SD = 10.11; E-: mean = 64.37, SD = 10.48), educational level (E+: mean = 8.82, SD = 3.73; E-: mean = 9.94, SD = 4.13), illness onset (E+: mean = 74.28, SD = 108.48; E-: mean = 66.35, SD = 51.52) and global cognitive impairment (MMSE scores E+: mean = 24.38, SD = 3.71; E-: mean = 26.27, SD = 3.30; MoCA scores E+: mean = 18.74, SD = 4.28; E-: mean = 21.66, SD = 5.97). The percentage patients with the delusion after RBD (43%) does not differ statistically from the one due to LBD (29%). The percentage and the severity of motor deficits (hemiplegia) were equally distributed in E+ (87%, 2.49) and E- groups (95%, 0.95) and unawareness for this deficit, as well as asomatognosia, were not present in the whole sample. The percentage and the severity of tactile deficits (hemianaesthesia) in the E+ group (97%, 2.28) were significantly higher (p<.01) than the percentage and the severity of hemianaesthesia in E- patients (51%, 1.14). Moreover, the percentage and the severity of proprioceptive deficits in the E+ group (100%, 1) were significantly higher (p<.01) than the percentage and the severity of proprioceptive deficits in the E- group (50%, 0.5). In addition, anosognosia for hemianaesthesia wassignificantly more frequent (p<.0001) in the E+ (70%) than in E- (18%) groups. Similarly, in the E+ group the percentage and the severity of both extrapersonal (88%; BITC mean score = 82.03; BITB mean score = 44.12) and personal (24%; Fluff test mean = 0.96) neglect were significantly higher (p<.001) than the percentage of extrapersonal (32%; BITC mean score = 126.55; BITB mean score = 69.31) and personal (7%; Fluff test mean score = 0.39) neglect in E- patients. The 15% of E+ patients displayed also somatoparaphrenia. All the above-mentioned statistical comparisons were performed on the number of patients with available data for each specific neuropsychological deficit.

- Figure 3 about here -

3.2. Embodiment of the alien arm movement

Clinical subgroups were obtained by means of an agglomerative hierarchical cluster analysis on the percentage of yes/no answers to the question *"Did your own left (or right) hand reach the cube?"* along all the conditions of the assessment. Mann-Whitney U Tests were employed for the between-groups comparisons along the assessment subparts. In the PM set of conditions, we manipulated the authorship of a passive reaching movement (see figure 2A). In the AM conditions, we manipulated the authorship of an active reaching movement (see figure21B).

In the preliminary phase, all patients were 100% correct to report the number of arms on the table as well as to name the color of three wooden cubes. In sixty-five RBD patients, the cluster analysis yielded two groups, one of twenty-nine E+ patients and the other of thirty-four E- patients. As regards twelve LBD patients, the cluster analysis yielded two groups, one of four E+ patients and the other of eight E- patients (see table 1).As for the embodiment of an external object, statistical analyses along conditions (see below) showed in each group, and in each condition that the mean percentage of yes/no answers to the question *"Did your own left (or right) hand reach the cube?"* were always either > 95% (i.e., the patients reported more than 95% of times that they reached the cube with their own hand/the patients reported less than5% of times that they did not reach the cube with their own hand) or < 5% (i.e., the patients reported less than 5% of times that they reached the cube with their own hand/the patients reported more than 95% of times that they did not reach the cube with their own hand). For this reason, those results were graphically represented in categorical terms (i.e., **✓ = > 95%/< 5%** and **X = < 5%/> 95%**) rather than in percentage.

In the PM set of conditions (see figure 2A), in RBD patients, the percentages of yes was significantly ($p < .0001$) lower in E+ (mean= 1.25, SD= 3.81) respect to E- (mean= 100, SD= 0) groups in condition 1, and significantly ($p < .0001$) higher in E+ (mean= 97.91, SD= 9.33) than in E- (mean= 0, SE= 0) group in condition 3. In LBD patients, the percentages of yes was significantly ($p < .001$) lower in E+ (mean= 3.13, SD= 6.25) than in E- group (mean= 100, SD= 0) in condition 1, and significantly ($p < .001$) higher in E+ (mean= 96.88, SD= 6.25) than in E- group (mean= 0, SE= 0) in condition 3 (see figure 4A). These data show that if both the patient's and the co-experimenter's correspondent arms are present and if the co-experimenter's arm is internal/parallel to the patients' real arm, E+ patients attribute to themselves passive movements of the co-experimenter's arm (and to the co-experimenter their own passive movements).

In the AM set of conditions (see figure2B), in RBD patients, the percentage of yes was significantly ($p < .0001$) higher in E+ (mean= 96.25, SD= 11.44) with respect to E- (mean= 0, SD= 0) group in condition 7. In LBD patients, the percentage of yes was significantly ($p < .001$) higher in E+ (mean= 93.75, SD= 7.22) respect to E- group (mean= 0, SD= 0) in condition 7 (see figure 4). These findings demonstrate that if both the patient's and the co-experimenter's correspondent arms are present and if the co-experimenter's arm is internal/parallel to the patients' real arm, E+ patients attribute to themselves active movements of the co-experimenter's arm (and to the co-experimenter their own active movements, when possible).

- Figure 4 about here -

4. Lesion comparison

As first, we compared the lesional pattern of the two groups (twenty-five E+ and thirty E-) identified by the cluster analysis (Figure 5, left part of the panel). Then, we repeated the analysis on two equal groups (fifteen E+ and fifteen E-) paired for the other concomitant deficits (Figure 5, right part of the panel). The two equal groups were paired (unpaired t- test) for each neurological/neuropsychological test (i.e., Mini Mental State Examination, neurological examination, proprioceptive deficits, anosognosia for hemiplegia, anosognosia for tactile deficits, somatoparaphrenia and unilateral neglect) except that for the presence/absence of the delusion. The two between-groups comparisons were obtained by means of a voxel-by-voxel Liebermeister test ($p < .01$ uncorrected) as implemented in the NPM included in MRIcron (Rorden et al., 2007). No significant difference was observed in the total volumes of the lesions in the two groups in both comparisons (two-sample *t*-test). Quantitative estimates of grey and white matter regions involvement were obtained by superimposing the Anatomical Labelling map template AAL and the JHU-white matter template.

With respect to the first analysis (left part of the panel), figure54A shows the lesion overlapping of E+ groups. The insula, the middle/superior temporal gyrus, the inferior frontal operculum, the rolandic operculum, the putamen, the pallidum, the external capsule, the posterior limb of the internal capsule the superior/posterior corona radiata and the superior longitudinal fascicules were damaged in more than 30% percent of the E+ patients. The insula, the rolandic operculum, the putamen, the external capsule, the posterior limb of the internal capsule and the superior corona radiata were damaged in more than 30% of the E- patients. Figure 5B shows the lesion plot subtraction between the two groups. The middle/superior temporal gyrus, the superior/posterior corona radiata and the superior longitudinal fasciculus were damaged at least the 30% more frequently in the E+ group with respect to the E- group. Figure 5C and Figure 5D display the results of the voxel-by-voxel test comparison and shows a lesional cluster for the E+ group centered on the middle/superior temporal gyrus, inferior frontal operculum, the middle frontal gyrus, the superior longitudinal fasciculus and the posterior/superior corona radiata.

As regards the second analysis (right part of the panel), Figure 5A shows that in the E+ group, the middle/superior temporal gyrus, the inferior frontal operculum, the rolandic operculum, the insula, the putamen, the pallidum, the eternal capsule, the posterior limb of the internal capsule the superior/posterior corona radiata and the superior longitudinal fasciculus were damaged in more than thirty percent of the patients. In the E- group, the external capsule, the insula, the putamen, the superior corona radiata were damaged in more than thirty percent of the patients. Figure 5B (left part) showed that the superior/posterior corona radiata and the superior longitudinal fascicules were damaged at least the thirty percent more frequently in the E+ than in the E- group. Figure 5C and Figure 5D represent the results of the voxel-by-voxel test and shoed a lesional cluster for the E+ group centered on the superior longitudinal fasciculus and the posterior/superior corona radiata.

- Figure 5 about here –

5. Discussion

Here, we investigated the clinical and anatomo-functional features of a neurologically-based delusion of body ownership. Almost a third of the whole sample showed embodiment of an alien arm presented in an anatomically-correct position. In the hemiplegic patients, this was associated to the embodiment of passive and active movements of the alien arm. Moreover, the delusion was associated to primary proprioceptive deficits and to damages of the corona radiata and the superior longitudinal fasciculus.

As regards the clinical presentation of the delusion and its association with other deficits, important considerations can be drawn from our sample. With respect to the lateralization, no significant difference was found between left and right lesions (despite our sample is being biased by the exclusion of several LBD patients because of language comprehension problems). With respect to the clinical association, whereas frequency/severity of motor deficits are equally distributed between E+ and E- patients, tactile deficits, their unawareness and neglect are more common in the patients with the body delusion. However, the presence of double dissociations in our sample indicate that these deficits are not necessary for the presence of the body delusion (it is worth noticing that neglect did not prevent the ability to identify the objects on the table). Proprioceptive deficits are always associated to the pathological embodiment but their presence also in patients without the delusion suggests that they are necessary but not sufficient for the pathological embodiment to occur. With respect to somatoparaphrenia, the large majority of E+ patients did not display any explicit form of disownership during the assessment. Indeed, when only the own arms were present, they correctly identified their contralesional hand as own without spontaneously reporting delusional beliefs. However, when also the alien arm was presented (under specific constraints), E+ patients not only misidentified the alien hand as their own but also misattributed their own hand to the other person, thus showing an explicit sense of disownership. The coexistence of the two delusional beliefs here (i.e., disownership of the own hand and ownership of an alien hand) might suggest that these two forms of body delusion could share some common mechanisms, as supported by the fact that the neural correlates of somatoparaphrenia (Gandola et al., 2012) are in part similar to those we report here (i.e., an important involvement of white matter and subcortical grey matter structures). Here we speculate that the two bodily delusions might represent different temporal stages of the same clinical evolution. This claim is in line with the fact that somatoparaphrenia is usually observed within the first week from the stroke (Vallar & Ronchi, 2009), whereas our E+ patients were assessed in the sub-acute or chronic phase of the illness (as average, the mean evaluation was obtained 74.22 days after the onset. However, we must clearly point out that hitherto no studies compared acute/sub-acute/chronic phases of the delusion. Hence, future investigations tracking different manifestation of the disease along time are barely required in order to support the above-mentioned hypothesis or, rather, the alternative, namely that delusional ownership and somatoparaphrenia are two completely different disorders of bodily awareness. With respect to anosognosia for hemiplegia which, as somatoparaphrenia, is more frequent in the acute phase (Fotopoulou, Pernigo, Maeda, Rudd, & Kopelman, 2010; Piedimonte, Garbarini, Pia, Mezzanato, & Berti, 2016; Piedimonte et al., 2015; Vocat, Staub, Stroppini, & Vuilleumier, 2010), in our sample is present only in one case (despite E+ patients experienced illusory willed movements when the alien embodied hand moved). As shown by these clinical data, our protocol is useful for testing the integrity of body awareness even when the classical assessment of somatoparaphrenia, anosognosia, personal neglect and asomatognosia does not show any apparent disorder. Being made of two separate parts with the first assessing the embodiment of an external object and the second assessing the embodiment over an alien arm movement, this protocol allows detecting residual disorders of body awareness and/or their more covert expressions. In particular, it evaluates the role of different available objects, as well as their congruency in terms of posture or body-like appearance on the embodiment of an external object. The second part allows assessing whether and how voluntariness and authorship of a reaching movement induce the patient's feeling that an alien arm movement is actually performed by him/her.

With respect to the conditions under which the delusion occurs, it arises only when some constraints in terms of body-like appearance and posture are satisfied (Blanke, Slater, & Serino, 2015), that is, if the external object is a real human hand and is presented from a 1st person perspective, in an anatomically-correct position (and internally/parallel to the patients' real arm when both the patient's and the co-experimenter's correspondent arms are present). It is worth noting that these constraints are similar to those reported for the rubber hand illusion (RHI) paradigm, which is an experimentally-induced illusory embodiment of a real-sized rubber hand (Botvinick & Cohen, 1998; Burin et al., 2017; Burin et al., 2019; Costantini & Haggard, 2007; Fossataro, Bruno, Giurgola, Bolognini, & Garbarini, 2018; Lenggenhager, Scivoletto, Molinari, & Pazzaglia, 2013; Longo, Schuur, Kammers, Tsakiris, & Haggard, 2008; Pyasik, Salatino, & Pia, 2019; Tsakiris, 2010; Zeller, Litvak, Friston, & Classen, 2015). However, the pathological embodiment is triggered by vision only whereas the RHI requires concurrent multisensory stimulations (but see, for instance (Rohde, Di Luca, & Ernst, 2011), showing the illusion triggered by vision of the fake hand only), and E+ patients actually believe that the alien hand is their own hand (whereas in the RHI, the experience is an *as if* feeling of owning the fake hand). Furthermore, even if previous studies successfully employed the RHI paradigm in stroke populations (Burin et al., 2015; Martinaud et al., 2017; Zeller et al., 2011), the delusion seems to emerge with real human hands (i.e., the subset of E+ patients which, in our sample, also viewed a prosthetic rubber hand did not show the phenomenon). The spared distinction between human and artificial categories (Kriegeskorte et al., 2008) suggests that a mechanism detecting natural and man-made objects has a fundamental role in the construction of human body ownership. The pathological embodiment is not limited to a static alien hand, it extends to its passive movements (whereas the patient's passive movements are attributed to the other person). The same happens if the patient is asked to perform voluntary movements (but it is the alien arm that actually moves): they misattribute to the co-experimenter's movement to their own will. This is in keeping with existing evidence in healthy subjects showing how an experimentally induced illusory ownership of an external object can generate an illusory authorship over its movements (Banakou & Slater, 2014; Burin et al., 2018; Kilteni & Ehrsson, 2017). These data, in turn, support the view that to some extent, body ownership acts upon motor consciousness (Pyasik, Furlanetto, & Pia, 2019) and this, hence, might explain the fact that the delusion is present in both dynamic and static conditions (see (Pia et al., 2016) for a full discussion on this point).

As regards the neural correlates of the delusion, although the nature of lesion mapping technique imposes *per se* caution, our two analyses (i.e., unpaired and paired groups for concomitant deficits) gave rise to a common lesional pattern in E+ patients: white matter tracts connecting premotor cortex to the posterior areas (i.e., the superior longitudinal fasciculus) and ascending/descending fibers up-to and from the cortex (i.e., the posterior/superior corona radiate). Interestingly, other studies have shown that deficit in specific awareness domains (e.g., anosognosia for hemiplegia; (Pacella et al., 2019) might, at least in part, rely on lesions disconnecting structures related to different aspects of body-monitoring, all necessary for the construction of a coherent sense of self. An influential neurocognitive model of body ownership, mainly based on the rubber hand illusion paradigm (Maselli & Slater, 2013; Tsakiris, 2010), states that body ownership arises from the comparison between actual perception of the body (rooted on converging visual, tactile, proprioceptive, sensorimotor, kinesthetic and efferent signals which constantly reaches the body) and internal preexisting representations of the body (which bind what may or may not be in principle part of one's body). At the neural level, it is thought that such process of comparing actual experience of the own body with its internal representation is subserved by a brain network including the anterior/posterior parietal cortex, the premotor cortex, the insular cortex and their connections (Tsakiris, 2010). Among them, the ventral premotor cortex and its connections with the posterior regions have a key role in multisensory integration since they are activated during the RHI (Ehrsson, Holmes, & Passingham, 2005; Guterstam et al., 2019; Makin, Holmes, & Ehrsson, 2008) and impairments to these structures are associated to RHI failure in stroke patients (Zeller et al., 2011). Furthermore, the functional connectivity between premotor cortex and visual areas involved in body part recognition (e.g., lateral occipitotemporal cortex and extrastriate body area) is modulated during the RHI (Limanowski & Blankenburg, 2015). This might be consistent with the fact that both the RHI and the delusion of ownership require either a decrease or a complete neglect of the objective dissimilarities between the own and the external object in order to occur. Based on this model, we suggest that in E+ patients a damage to the white matter tracts connecting anterior and posterior part of the brain would prevent internal representations of the body to receive information resulting from multisensory integration process. Hence, patients would embody external object (and its movements) only if its visual features are compatible in terms of shape (it must be an hand), natural category (it must be a real hand), identity (it must correspond to the affected right or left hand) and posture (it must be in a body compatible position) with spared preexisting body representation.

In conclusion, the delusion has a clear-cut clinical picture and might be explained as a disconnection deficit, mainly involving white matter tracts. Importantly, the proposed evaluation can be considered as an effective tool to assess disorders of body awareness, even in their more covert expressions.

Acknowledgments

The authors are grateful to all of the patients involved in the study.

Funds

This work has been funded by MIUR-SIR 2014 grant (RBSI146V1D), a San Paolo Foundation 2016 grant (CSTO165140) to F.G, and by a 2014-2016 Turin University Grant (ex 60%) to L.P.

Figure and tables legends

Table 1. Demographical, clinical and neuropsychological data of the patients. Id = patients' Identification number. Gen = Gender (M = Male, F = Female). El = Education Level (years of formal education). Han = Handedness (R = right, L = left). Aet = Aetiology (H= hemorrhage, I= ischemia). Sid = Lesion side (R = right, L = Left). Ons = Onset (days between the disease and the first day of the assessment). MMSE = Mini Mental State Examination (0-30). EN = Neurologic Examination for the contralesional upper limb (M = Motor deficits, T = Tactile deficits, D = distal, P = Proximal), 0= absence, 1-3 presence, ≥ 2 hemiplegia or hemianaesthesia; P = Proprioceptive deficits, 0 = absence, 1 = presence). AHP = Anosognosia for hemiplegia for the contralesional upper limb (0 = absence, 1 = presence; tested only in patients with severe motor deficits (hemiplegia), that is ≥ 2). AHA = Anosognosia for tactile deficits on the contralesional upper limb (0 = absence, 1 = presence; tested only in patients with severe tactile deficits (hemianaesthesia), namely ≥ 2). Sop = Somatoparaphrenia (0 = absence, 1 = presence). Aso = Asomatognosia (0 = absence, 1 = presence). UN = Unilateral Neglect; Ext = Extrapersonal neglect (BIT = Behavioral Inattention Test, 0-227, cut-off ≥ 196, Per = Personal neglect; Flu = Fluff test (0-3 cut-off ≥ 2). PE = Pathological Embodiment (EO = External Object; AAM Alien Arm Movement). E+ = patients with the embodiment, E- = patients without the embodiment. LS = patients which participated in the lesion subtraction analysis, + = patients with the body delusion, - = patients without the delusion). n.e. = not executable. n.a. = not applicated.

Figure 1. Embodiment of the external object assessment. the patient’s arm(s) and/or the co-experimenter’s arm or a neutral object were present on the table in different positions with colored cubes in front of them. Patients had to identify their own hands by answering the question: *“What is the color of the cube that is currently in front of your left (right) hand?”; Quale è il colore del cubo che in questo momento è di fronte alla sua mano sinistra (o destra)?”*.

Figure 2. Embodiment of alien arm movement assessment. Both the patient’s arms and one co-experimenter’s arm were present on the table in different positions and different colored cubes were

placed vertically aligned with respect to the patient's midline at a reaching distance. The patient's or the co-experimenter's arm were passively moved by the examiner or they had to actively move to reach the cube. Patients had to identify their own reaching movements by answering the question: "*Did your own left (or right) hand reach the cube?; La sua mano sinistra (o destra) ha raggiunto il cubo?"*.**Figure 3.** Results for the embodiment of the external object assessment plotted as categories (i.e., ✓ and **X**). The mark ✓ below a given hand (or spoon) indicates that the color in front of that object it has been reported > 95% of times, whereas X indicates that the color in front of that object it has been reported < 5% of time (answer to the question "*What is the color of the cube that is currently in front t of your left (right) hand?"*).

Figure 4. Results for the embodiment of the embodiment of alien arm movement assessment plotted as categories (i.e., ✓ and **X**). The mark ✓ below a given hand indicates that the own hand is reported more than 95% as having reached the cube/the own hand is not reported less than 5% as having reached the cube), whereas X indicates that the own hand is reported less than 5% as having reached the cube/the own hand is not reported more than 95% as having reached the cube (answer to the question *"Did your own left (or right) hand reach the cube?"*).

Figure 5. Lesion mapping of unpaired (left part of the panel) and paired (right part of the panel) E+ and E- groups. **A** Overlays of regional lesion plots of the two groups. The frequency is represented trough a color scale ranging from black (lesion in at least one patient) to red (lesion in eighteen patients); **B** Subtraction of regional lesion plots. The percentages of regions damaged more frequently in the E+ group respect to the E- group are displayed trough a color scale ranging from black to red. **C** Brain regions significantly associated to the E+ group. All voxels which survived to the binomial test (p <.01 uncorrected) are displayed. The color scale represents Z- Libermeister scores. MNI Z coordinates of each transverse section are reported. **D** Quantitative estimate of the brain structures significantly associated to the delusion (E+ group vs E- group). For each brain

structure, the number of clustering voxels, Libermeister-score, and MNI coordinates of the center of mass are reported

										EN									UN		PE		
Id	**Age**	**Gen**	**El**	**Han**	**Aet**	**Side**	**Ons**	**MOCA**	**MMSE**	**M**		**T**		**P**	**AHP**	**AHA**	**Sop**	**Aso**	**Ext BIT**	**P Flu**	**EO**	**AA**	**LS**
										D	**P**	**D**	**P**										
1	83	F	13	R	I	R	45	21	n.a.	2	3	0	0	0	n.a.	n.e.	0	0	n.a.	n.a.	E-	E-	n.e.
2	65	M	13	R	I	R	20	n.a.	n.a.	0	0	1	1	0	n.e.	n.e.	0	0	n.a.	n.a.	E-	n.e.	n.e.
3	63	M	10	R	I	R	32	28	30	3	3	0	0	0	n.a.	n.e.	0	0	226	n.a.	E-	E-	n.e.
4	59	M	18	R	I	R	112	n.a.	28	1	1	1	1	1	n.e.	n.e.	0	0	224	0	E-	n.e.	n.e.
5	55	M	13	R	I	R	36	17	23.2	3	3	3	3	1	0	1	0	0	87	0	E+	E+	n.e.
6	78	F	5	R	I	R	72	n.a.	26	3	3	0	0	0	0	n.e.	0	0	228	0	E-	E-	n.e.
7	81	F	5	R	I	R	47	n.a.	27	1	1	0	0	0	n.e.	n.e.	0	0	223	n.a.	E-	n.e.	n.e.
8	76	M	5	R	I	L	43	n.a.	n.a.	3	3	3	3	1	0	n.a.	0	0	n.a.	n.a.	E+	E+	n.e.
9	86	F	5	R	H	L	61	15	25	1	1	1	1	0	n.e.	n.e.	0	0	189	0	E-	n.e.	n.e.
10	51	M	10	R	I	R	180	29	n.a.	2	1	1	1	0	0	n.e.	0	0	221	n.a.	E-	n.e.	n.e.
11	49	F	18	R	H	R	70	10	n.a.	2	3	1	1	1	0	n.e.	0	0	n.a.	n.a.	E-	E-	n.e.
12	62	F	8	R	I	L	180	27	n.a.	3	2	0	0	0	0		0	0	n.a.	n.a.	E-	E-	n.e.
13	62	F	8	R	I	R	30	21	28	3	3	3	3	1	n.a.	1	0	0	108	n.a.	E+	E+	+
14	79	M	13	R	I	R	31	21.3	22.1	3	3	3	0	1	0	1	0	0	199	n.a.	E+	E+	n.e.
15	53	M	13	R	H	R	43	26	n.a.	3	3	3	3	1	n.a.	0	0	0	209	n.a.	E-	ME-	-
16	71	M	11	R	H	L	69	10	14	1	1	n.a.	n.a.	n.a.	n.e.	n.a.	0	0	n.a.	n.a.	E-	n.e.	n.e.
17	60	F	13	R	I	R	60	30	n.a.	1	1	1	1	1	n.e.	n.e.	0	0	181	n.a.	E-	n.e.	-
18	80	F	8	R	I	R	52	n.a.	n.a.	3	3	3	3	1	0	0	0	0	37	n.a.	E-	E-	-
19	82	M	13	R	I	L	48	19	26	3	3	0	0	1	0	n.e.	0	0	n.a.	n.a.	E-	E-	n.e.
20	77	F	17	R	H	R	35	n.a.	28	3	3	3	3	1	0	0	0	0	213	0	E+	E+	+
21	63	F	13	R	H	R	69	n.a.	n.a.	3	3	2	2	1	0	1	0	0	n.a.	n.a.	E+	E+	n.e.
22	85	M	5	R	I	R	36	n.a.	24.4	3	3	3	1	1	n.a.	1	0	0	81	n.a.	E+	E+	n.e.
23	85	F	11	R	I	R	51	25	28	3	3	1	1	n.a.	0	n.e.	0	0	190	0	E+	E+	+
24	64	M	17	R	I	R	50	n.a.	25	3	3	1	1	1	0	n.e.	0	0	175	2	E+	E+	+
25	83	M	3	R	I	R	30	n.a.	25.5	3	3	0	0	0	0	n.e.	0	0	226	0	E-	E-	n.e.
26	69	F	5	R	H	L	40	n.a.	n.a.	1	1	2	1	1	n.e.	0	0	0	163	2	E-	n.e.	n.e.
27	75	F	12	R	H	R	68	n.a.	18	2	2	2	2	1	0	1	1	0	17	2	E+	E+	n.e.
28	51	F	13	L	I	R	72	25	26	3	3	0	0	0	0	n.e.	0	0	225	0	E-	E-	n.e.

29	74	M	8	R	I	L	56	18	28	3	3	0	0	0	0	n.e.	0	0	n.a.	n.a.	E-	E-	n.e.
30	70	M	8	R	I	R	68	15	n.a.	3	3	3	3	1	n.a.	1	0	0	105	n.a.	E+	E+	n.e.
31	45	M	5	R	H	R	87	n.a.	26.2	3	3	3	3	1	0	1	0	0	137	0	E+	E+	+
32	66	M	7	R	I	R	57	24	n.a.	3	1	0	0	0	n.a.	n.e.	0	0	121	1	E-	n.e.	-
33	74	F	8	R	I	R	69	15	n.a.	0	0	3	3	1	n.e.	0	0	0	150	n.a.	E+	n.e.	n.e.
34	58	F	12	R	H	L	85	10	n.a.	2	3	2	2	1	n.a.	0	0	0	n.a.	n.a.	E-	E-	n.e.
35	63	M	13	R	H	R	70	27	n.a.	3	3	0	0	0	0	n.e.	0	0	n.a.	n.a.	E-	E-	n.e.
36	62	M	11	R	I	R	60	24	26	0	0	1	1	1	n.e.	n.e.	0	0	107	n.a.	E+	n.e.	n.e.
37	79	F	13	R	I	R	90	n.a.	24	3	3	3	3	1	0	0	0	0	221	0	E-	E-	-
38		F	8	R	I	R	69	n.a.	n.a.	3	3	3	3	n.a.	n.a.	0	n.a.	n.a.	n.a.	n.a.	E-	E-	n.e.
39	85	F	8	R	I	R	200	n.a.	21.2	3	3	3	3	1	0	1	0	0	n.a.	n.a.	E+	E+	n.e.
40	57	M	14	R	H	L	49	17	n.a.	3	3	1	1	1	n.a.	n.e.	0	0	176	3	E+	E+	n.e.
41	66	M	5	R	I	R	370	17	n.a.	3	3	0	0	1	0	n.e.	n.a.	n.a.	192	n.a.	E-	E-	-
42	73	M	11	R	I	R	26	n.a.	24.4	3	3	3	3	1	0	1	0	0	90	0	E+	E+	+
43	75	F	8	R	I	R	48	16	19.7	3	3	1	1	1	n.a.	n.e.	1	0	113	n.a.	E+	E+	n.e.
44	68	M	5	R	I	R	40	n.a.	25	3	3	3	3	1	0	1	0	0	15	3	E+	E+	n.e.
45	73	F	8	R	H	R	700	n.a.	24.6	0	0	1	1	1	n.e.	n.e.	0	0	193	n.a.	E+	n.e.	n.e.
46	63	M	13	R	I	R	51	25	25	1	1	0	0	0	n.e.	n.e.	0	0	224	n.a.	E-	n.e.	n.e.
47	65	F	8	R	I	R	40	24	28	3	3	3	3	1	0	0	0	0	188	0	E-	E-	-
48	67	M	8	R	I	R	46	21	25	1	1	0	0	0	n.e.	n.e.	0	0	214	0	E-	n.e.	n.e.
49	69	F	8	R	H	L	35	10	n.a.	1	1	3	3	1	n.e.	1	0	0	n.a.	0	E+	n.e.	n.e.
50	70	M	3	R	I	R	70	n.a.	23	2	2	0	0	n.a.	0	n.e.	0	0	112	0	E+	E+	+
51	78	M	8	R	I	R	60	n.a.	29	0	0	3	3	1	n.e.	1	0	0	92	0	E+	n.e.	n.e.
52	59	M	8	R	I	R	43	22	n.a.	3	3	1	0	1	n.a.	0	0	0	n.a.	3	E-	E-	n.e.
53	57	F	13	R	I	R	63	n.a.	25	3	3	3	3	1	0	0	0	0	135	0	E+	E+	+
54	72	M	8	R	I	L	45	24	27.4	3	3	3	3	1	0	0	0	0	192	0	E+	E+	+
55	79	F	8	R	I	R	42	17	n.a.	0	0	1	3	1	n.e.	0	0	0	129	2	E+	n.e.	n.e.
56	55	M	5	R	I	R	30	n.a.	17.9	3	3	2	2	1	0	1	1	0	25	3	E+	E+	n.e.
57	75	F	5	R	I	R	32	20	26.7	2	2	2	0	0	0	n.e.	0	0	208	0	E-	E-	n.e.
58	65	M	5	R	H	R	35	n.a.	n.a.	2	1	1	1	1	0	n.e.	0	0	n.a.	n.a.	E+	n.e.	n.e.
59	77	F	5	R	I	L	60	7	n.a.	3	3	0	0	0	0	n.e.	0	0	n.a.	n.a.	E-	E-	n.e.
60	44	F	8	R	H	R	69	18	n.a.	3	3	3	3	1	n.a.	1	0	0	n.a.	n.a.	E-	E-	n.e.
61	65	F	5	R	I	L	39	14	19.9	3	3	3	3	1	0	0	0	0	222	0	E-	E-	n.e.

62	68	M	8	R	I	R	30	n.a.	28	3	3	2	2	1	0	0	0	0	210	1	E-	E-	-
63	62	M	5	R	H	R	76	n.a.	28	3	3	0	0	0	0	n.e.	0	0	228	0	E-	E-	n.e.
64	67	F	13	R	H	L	26	24	n.a.	3	3	0	0	0	0	n.e.	0	0	n.a.	n.a.	E-	E-	n.e.
65	69	M	19	R	I	R	91	n.a.	26	3	3	0	0	0	0	n.e.	0	0	220	0	E-	E-	-
66	63	M	5	R	I	R	34	18	n.a.	3	3	0	0	0	0	n.e.	0	0	215	n.a.	E-	E-	n.e.
67	69	M	8	R	I	R	60	n.a.	27	3	3	1	1	1	0	n.e.	0	0	213	0	E+	E+	+
68	67	M	13	R	H	L	48	21	n.a.	0	0	0	0	1	n.e.	n.e.	0	0	n.a.	n.a.	E-	n.e.	n.e.
69	75	F	8	R	I	R	69	n.a.	24	3	3	3	0	1	n.a.	1	1	0	19	3	E+	E+	n.e.
70	70	F	8	R	I	R	70	n.a.	25	3	3	3	3	1	0	0	1	0	88	3	E+	E+	+
71	50	F	8	L	H	L	180	n.a.	17	3	3	3	3	1	0	0	0	0	170	0	E+	E+	n.e.
72	64	M	5	R	I	R	40	n.a.	26	3	3	2	2	1	0	1	0	0	217	0	E-	E-	-
73	59	M	13	R	H	R	75	23	n.a.	3	3	3	3	1	n.a.	0	0	0	n.a.	n.a.	E-	E-	n.e.
74	75	M	5	R	I	R	34	18	n.a.	3	3	3	3	n.a.	n.a.	1	0	n.a.	125	n.a.	E+	E+	n.e.
75	74	F	5	R	I	R	60	n.a.	16	3	3	3	3	1	0	0	0	0	123	3	E+	E+	+
76	65	M	8	R	I	R	50	n.a.	28	3	3	3	3	1	0	1	0	0	156	0	E-	E-	-
77	64	M	8	R	I	L	30	17	26	3	3	0	0	0	0	n.e.	0	0	195	0	E-	E-	n.e.
78	57	F	8	R	I	R	75	28	n.a.	0	0	0	0	1	n.e.	n.e.	0	0	n.a.	n.a.	E-	n.e.	n.e.
79	61	M	17	R	H	R	105	27	n.a.	2	2	3	3	1	n.a.	0	0	0	225	1	E-	E-	n.e.
80	58	M	8	R	H	R	63	22	n.a.	3	3	3	3	1	n.a.	1	1	0	38	n.a.	E+	E+	n.e.
81	67	F	10	R	I	R	27	27	n.a.	3	3	1	1	0	0	n.e.	0	0	218	0	E-	E-	n.e.
82	37	F	18	R	I	R	50	n.a.	30	3	3	3	3	1	0	0	0	0	144	0	E-	E-	-
83	48	M	13	R	I	R	101	n.a.	30	3	3	0	0	0	0	n.e.	0	0	226	0	E-	E-	n.e.
84	63	M	13	R	I	R	97	24	n.a.	1	1	0	0	1	n.e	n.e	0	0	223	n.a.	E-	n.e.	n.e.
85	62	F	8	R	I	R	40	n.a.	28	3	3	3	3	1	0	1	0	0	112	0	E-	E-	-
86	50	F	18	R	I	R	40	n.a.	29	3	3	3	3	1	0	1	0	0	218	0	E+	E+	n.e.
87	55	F	18	R	I	R	41	30	29	3	3	1	1	0	0	n.e.	0	0	224	0	E-	E-	n.e.
88	75	M	8	R	I	R	69	n.a.	n.a.	3	3	0	0	0	0	n.e.	0	0	39	0	E-	E-	-
89	82	M	8	R	I	R	45	n.a.	27	3	3	2	2	1	0	1	0	0	135	0	E+	E+	+
90	72	F	5	R	I	R	60	n.a.	28	3	3	1	1	1	0	1	0	0	126	0	E+	E+	+
91	56	M	8	R	I	R	69	30	n.a.	3	3	3	3	1	n.a.	0	0	0	n.a.	n.a.	E-	E-	n.e.
92	55	M	5	R	H	R	35	21	n.a.	1	1	3	0	1	0	0	n.a.	n.a.	205	3	E-	n.e.	n.e.
93	61	M	8	R	H	R	65	26	n.a.	3	3	0	0	n.a.	0	n.e.	0	0	221	n.a.	E-	E-	-
94	68	F	13	R	H	R	38	27	n.a.	3	3	3	3	1	0	0	0	0	223	0	E-	E-	n.e.

95	75	F	5	R	I	R	40	n.a.	28	3	3	2	2	1	0	1	0	0	149	0	E+	E+	+
96	45	M	13	R	I	R	60	23	n.a.	3	2	0	0	0	0	n.e.	0	0	n.a.	n.a.	E-	E-	n.e.

References

Banakou, D., & Slater, M. (2014). Body ownership causes illusory self-attribution of speaking and influences subsequent real speaking. *Proceedings of the National Academy of Sciences of the United States of America, 111*(49), 17678-17683. doi: 10.1073/pnas.1414936111

Berti, A., Garbarini, F., & Pia, L. (2015). Action Generation, Intention, and Agency in Motor and Body Awareness Deficits. In P. Haggard & B. Eitam (Eds.), *The Sense of Agency* (pp. 371-388). New York (U.S.A.): Oxford University Press.

Bisiach, E., & Faglioni, P. (1974). Recognition of random shapes by patients with unilateral lesions as a function of complexity, association value and delay. *Cortex, 10*(2), 101-110.

Bisiach, E., Vallar, G., Perani, D., Papagno, C., & Berti, A. (1986). Unawareness of disease following lesions of the right hemisphere: anosognosia for hemiplegia and anosognosia for hemianopia. *Neuropsychologia, 24*(4), 471-482.

Blanke, O., Slater, M., & Serino, A. (2015). Behavioral, Neural, and Computational Principles of Bodily Self-Consciousness. *Neuron, 88*(1), 145-166. doi: 10.1016/j.neuron.2015.09.029

Botvinick, M., & Cohen, J. (1998). Rubber hands 'feel' touch that eyes see. *Nature, 391*(6669), 756. doi: 10.1038/35784

Burin, D., Garbarini, F., Bruno, V., Fossataro, C., Destefanis, C., Berti, A., & Pia, L. (2017). Movements and body ownership: Evidence from the rubber hand illusion after mechanical limb immobilization. *Neuropsychologia, 107*, 41-47. doi: 10.1016/j.neuropsychologia.2017.11.004

Burin, D., Livelli, A., Garbarini, F., Fossataro, C., Folegatti, A., Gindri, P., & Pia, L. (2015). Are movements necessary for the sense of body ownership? Evidence from the rubber hand illusion in pure hemiplegic patients. *PLoS One, 10*(3), 1-12. doi: 10.1371/journal.pone.0117155

Burin, D., Pignolo, C., Ales, F., Giromini, L., Pyasik, M., Ghirardello, D., . . . Pia, L. (2019). Relationships Between Personality Features and the Rubber Hand Illusion: An Exploratory Study. *Frontiers in Psychology, 10,* 2762. doi: 10.3389/fpsyg.2019.02762

Burin, D., Pyasik, M., Ronga, I., Cavallo, M., Salatino, A., & Pia, L. (2018). "As long as that is my hand, that willed action is mine": Timing of agency triggered by body ownership. *Consciousness and Cognition*. doi: 10.1016/j.concog.2017.12.005

Costantini, M., & Haggard, P. (2007). The rubber hand illusion: sensitivity and reference frame for body ownership. *Consciousness and Cognition, 16*(2), 229-240. doi: 10.1016/j.concog.2007.01.001

Ehrsson, H. H., Holmes, N. P., & Passingham, R. E. (2005). Touching a rubber hand: feeling of body ownership is associated with activity in multisensory brain areas. *Journal of Neuroscience, 25*(45), 10564-10573. doi: 10.1523/JNEUROSCI.0800-05.2005

Feinberg, T. E., Haber, L. D., & Leeds, N. E. (1990). Verbal asomatognosia. *Neurology, 40*(9), 1391-1394.

Fossataro, C., Bruno, V., Bosso, E., Chiotti, V., Gindri, P., Farne, A., & Garbarini, F. (2020). The sense of body-ownership gates cross-modal improvement of tactile extinction in brain-damaged patients. *Cortex, 127,* 94-107. doi: 10.1016/j.cortex.2020.02.004

Fossataro, C., Bruno, V., Gindri, P., & Garbarini, F. (2018). Defending the Body Without Sensing the Body Position: Physiological Evidence in a Brain-Damaged Patient With a Proprioceptive Deficit. *Frontiers in Psychology, 9,* 2458. doi: 10.3389/fpsyg.2018.02458

Fossataro, C., Bruno, V., Gindri, P., Pia, L., Berti, A., & Garbarini, F. (2018). Feeling touch on the own hand restores the capacity to visually discriminate it from someone else' hand: Pathological embodiment receding in brain-damaged patients. *Cortex, 104,* 207-219. doi: 10.1016/j.cortex.2017.06.004

Fossataro, C., Bruno, V., Giurgola, S., Bolognini, N., & Garbarini, F. (2018). Losing my hand. Body ownership attenuation after virtual lesion of the primary motor cortex. *European Journal of Neuroscience, 48*(6), 2272-2287. doi: 10.1111/ejn.14116

Fossataro, C., Gindri, P., Mezzanato, T., Pia, L., & Garbarini, F. (2016). Bodily ownership modulation in defensive responses: physiological evidence in brain-damaged patients with pathological embodiment of other's body parts. *Scientific Reports, 6*, 27737. doi: 10.1038/srep27737

Fotopoulou, A., Jenkinson, P. M., Tsakiris, M., Haggard, P., Rudd, A., & Kopelman, M. D. (2011). Mirror-view reverses somatoparaphrenia: dissociation between first- and third-person perspectives on body ownership. *Neuropsychologia, 49*(14), 3946-3955. doi: S0028-3932(11)00476-3 [pii] 10.1016/j.neuropsychologia.2011.10.011

Fotopoulou, A., Pernigo, S., Maeda, R., Rudd, A., & Kopelman, M. A. (2010). Implicit awareness in anosognosia for hemiplegia: unconscious interference without conscious re-representation. *Brain, 133*(12), 3564-3577.

Gallagher, S. (2000). Philosophical conceptions of the self: implications for cognitive science. *Trends in Cognitive Sciences, 4*(1), 14-21. doi: S1364661399014175 [pii]

Gandola, M., Invernizzi, P., Sedda, A., Ferre, E. R., Sterzi, R., Sberna, M., . . . Bottini, G. (2012). An anatomical account of somatoparaphrenia. *Cortex, 48*(9), 1165-1178. doi: S0010-9452(11)00200-0 [pii] 10.1016/j.cortex.2011.06.012

Garbarini, F., Fornia, L., Fossataro, C., Pia, L., Gindri, P., & Berti, A. (2014). Embodiment of others' hands elicits arousal responses similar to one's own hands. *Current Biology, 24*(16), R738-739. doi: 10.1016/j.cub.2014.07.023

Garbarini, F., Fossataro, C., Berti, A., Gindri, P., Romano, D., Pia, L., . . . Neppi-Modona, M. (2015). When your arm becomes mine: Pathological embodiment of alien limbs using tools modulates own body representation. *Neuropsychologia, 70*, 402-413. doi: 10.1016/j.neuropsychologia.2014.11.008

Garbarini, F., & Pia, L. (2013). Bimanual coupling paradigm as an effective tool to investigate productive behaviors in motor and body awareness impairments. *Frontiers in Human Neuroscience, 7*(737), 1-5. doi: 10.3389/fnhum.2013.00737

Garbarini, F., Pia, L., Fossataro, C., & Berti, A. (2017). From pathological embodiment to a model for body awareness. In F. De Vignemont (Ed.), *The Subject's Matter: Self-Consciousness and the Body* (pp. 371-388). Cambridge (U.S.A.): The MIT Press.

Garbarini, F., Pia, L., Piedimonte, A., Rabuffetti, M., Gindri, P., & Berti, A. (2013). Embodiment of an alien hand interferes with intact-hand movements. *Current Biology, 23*(2), R57-58. doi: 10.1016/j.cub.2012.12.003

Gerstmann, J. (1942). Problem of imperception of disease and of impaired body territories with organic lesions. *Archives of Neurology and Psychiatry, 48*, 890-913.

Goble, D. J. (2010). Proprioceptive acuity assessment via joint position matching: from basic science to general practice. *Physical Therapy, 90*(8), 1176-1184. doi: 10.2522/ptj.20090399

Guterstam, A., Collins, K. L., Cronin, J. A., Zeberg, H., Darvas, F., Weaver, K. E., . . . Ehrsson, H. H. (2019). Direct Electrophysiological Correlates of Body Ownership in Human Cerebral Cortex. *Cerebral Cortex, 29*(3), 1328-1341. doi: 10.1093/cercor/bhy285

Halligan, P. W., Fink, G. R., Marshall, J. C., & Vallar, G. (2003). Spatial cognition: evidence from visual neglect. *Trends in Cognitive Sciences, 7*(3), 125-133. doi: S1364661303000329 [pii]

Karnath, H. O., Baier, B., & Nagele, T. (2005). Awareness of the functioning of one's own limbs mediated by the insular cortex? *Journal of Neuroscience, 25*(31), 7134-7138.

Kilteni, K., & Ehrsson, H. H. (2017). Body ownership determines the attenuation of self-generated tactile sensations. *Proceedings of the National Academy of Sciences, 114*(31), 8426-8431. doi: 10.1073/pnas.1703347114

Kriegeskorte, N., Mur, M., Ruff, D. A., Kiani, R., Bodurka, J., Esteky, H., . . . Bandettini, P. A. (2008). Matching categorical object representations in inferior temporal cortex of man and monkey. *Neuron, 60*(6), 1126-1141. doi: 10.1016/j.neuron.2008.10.043

Lenggenhager, B., Scivoletto, G., Molinari, M., & Pazzaglia, M. (2013). Restoring Tactile Awareness Through the Rubber Hand Illusion in Cervical Spinal Cord Injury. *Neurorehabilitation and Neural Repair, 27*(8), 704-708. doi: Doi 10.1177/1545968313491009

Limanowski, J., & Blankenburg, F. (2015). Network activity underlying the illusory self-attribution of a dummy arm. *Human Brain Mapping, 36*(6), 2284-2304. doi: 10.1002/hbm.22770

Longo, M. R., Schuur, F., Kammers, M. P., Tsakiris, M., & Haggard, P. (2008). What is embodiment? A psychometric approach. *Cognition, 107*(3), 978-998. doi: S0010-0277(08)00006-1 [pii] 10.1016/j.cognition.2007.12.004

Makin, T. R., Holmes, N. P., & Ehrsson, H. H. (2008). On the other hand: dummy hands and peripersonal space. *Behavioral Brain Research, 191*(1), 1-10. doi: S0166-4328(08)00113-7 [pii] 10.1016/j.bbr.2008.02.041

Martinaud, O., Besharati, S., Jenkinson, P. M., & Fotopoulou, A. (2017). Ownership illusions in patients with body delusions: Different neural profiles of visual capture and disownership. *Cortex, 87*, 174-185. doi: 10.1016/j.cortex.2016.09.025

Maselli, A., & Slater, M. (2013). The building blocks of the full body ownership illusion. *Frontiers in Human Neuroscience, 7*, 1-15.

Measso, G., Cavarzeran, F., Zappala, G., Lebowitz, B. D., Crook, T. H., Pirozzolo, F. J., . . . Grigoletto, F. (1993). The Mini-Mental State Examination: Normative study of an Italian random sample. *Developmental Neuropsychology, 9*(2), 77-85.

Nasreddine, Z. S., Phillips, N., & Chertkow, H. (2012). Normative data for the Montreal Cognitive Assessment (MoCA) in a population-based sample. *Neurology, 78*(10), 765-766. doi: 10.1212/01.wnl.0000413072.54070.a3

Newcomer, S. R., Steiner, J. F., & Bayliss, E. A. (2011). Identifying subgroups of complex patients with cluster analysis. *The American journal of managed care, 17*(8), e324-332.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*(1), 97-113.

Orfei, M. D., Robinson, R. G., Prigatano, G. P., Starkstein, S., Rusch, N., Bria, P., . . . Spalletta, G. (2007). Anosognosia for hemiplegia after stroke is a multifaceted phenomenon: a systematic review of the literature. *Brain, 130*(12), 3075-3090.

Pacella, V., Foulon, C., Jenkinson, P. M., Scandola, M., Bertagnoli, S., Avesani, R., . . . Thiebaut de Schotten, M. (2019). Anosognosia for hemiplegia as a tripartite disconnection syndrome. *Elife, 8*. doi: 10.7554/eLife.46075

Pia, L., Cavallo, M., & Garbarini, F. (2014). Anosognosia for hemianaesthesia: from the syndrome to tactile awareness. *Translational Neuroscience, 5*(3), 1-4. doi: 10.2478/s13380-014-0227-5

Pia, L., Garbarini, F., Burin, D., Fossataro, C., & Berti, A. (2015). A predictive nature for tactile awareness? Insights from damaged and intact central-nervous-system functioning. *Frontiers in Human Neuroscience, 9*, 287. doi: 10.3389/fnhum.2015.00287

Pia, L., Garbarini, F., Fossataro, C., Burin, D., & Berti, A. (2016). Sensing the body, representing the body: evidence from a neurologically based delusion of body ownership. *Cognitive Neuropsychology, 33*(1-2), 112-119. doi: 10.1080/02643294.2016.1185404

Pia, L., Garbarini, F., Fossataro, C., Fornia, L., & Berti, A. (2013). Pain and body awareness: evidence from brain-damaged patients with delusional body ownership. *Frontiers in Human Neuroscience, 7*(298), 1-9. doi: 10.3389/fnhum.2013.00298

Pia, L., Spinazzola, L., Garbarini, F., Bellan, G., Piedimonte, A., Fossataro, C., . . . Berti, A. (2014). Anosognosia for hemianaesthesia: a voxel-based lesion-symptom mapping study. *Cortex, 61*, 158-166. doi: 10.1016/j.cortex.2014.08.006

Piedimonte, A., Garbarini, F., Pia, L., Mezzanato, T., & Berti, A. (2016). From intention to perception: The case of anosognosia for hemiplegia. *Neuropsychologia, 87*, 43-53. doi: 10.1016/j.neuropsychologia.2016.03.007

Piedimonte, A., Garbarini, F., Rabuffetti, M., Pia, L., Montesano, A., Ferrarin, M., & Berti, A. (2015). Invisible Grasps: Grip Interference in Anosognosia for Hemiplegia. *Neuropsychology, 29*(5), 776-781. doi: 10.1037/neu0000182

Preston, C., & Newport, R. (2008). Was that me? The right hemisphere and the sense of agency: Embodiment of others and misattribution of self-generated action. In B. Hardy-Valle & N. Payette (Eds.), *Beyond the brain: Embodied, situated and distributed cognition,* (pp. 107-122). Newcastle: Cambridge Scholars Publishing.

Pyasik, M., Furlanetto, T., & Pia, L. (2019). The Role of Body-Related Afferent Signals in Human Sense of Agency. *Journal of Experimental Neuroscience, 13,* 1179069519849907. doi: 10.1177/1179069519849907

Pyasik, M., Salatino, A., & Pia, L. (2019). Do movements contribute to sense of body ownership? Rubber hand illusion in expert pianists. *Psychological Research, 83*(1), 185-195. doi: 10.1007/s00426-018-1137-x

Rohde, M., Di Luca, M., & Ernst, M. O. (2011). The Rubber Hand Illusion: feeling of ownership and proprioceptive drift do not go hand in hand. *PLoS One, 6*(6), 1-9. doi: 10.1371/journal.pone.0021659

Romano, D., & Maravita, A. (2019). The dynamic nature of the sense of ownership after brain injury. Clues from asomatognosia and somatoparaphrenia. *Neuropsychologia, 132,* 107119. doi: 10.1016/j.neuropsychologia.2019.107119

Ronga, I., Garbarini, F., Neppi-Modona, M., Fossataro, C., Pyasik, M., Bruno, V., . . . Pia, L. (2018). 'See Me, Feel Me': Prismatic Adaptation of an Alien Limb Ameliorates Spatial Neglect in a Patient Affected by Pathological Embodiment. *Frontiers in Psychology, 9*, 2726. doi: 10.3389/fpsyg.2018.02726

Rorden, C., Bonilha, L., Fridriksson, J., Bender, B., & Karnath, H. O. (2012). Age-specific CT and MRI templates for spatial normalization. *Neuroimage, 61*(4), 957-965. doi: 10.1016/j.neuroimage.2012.03.020

Rorden, C., Karnath, H. O., & Bonilha, L. (2007). Improving lesion-symptom mapping. *Journal of Cognitive Neuroscience, 19*(7), 1081-1088. doi: 10.1162/jocn.2007.19.7.1081

Sperber, C., & Karnath, H. O. (2016). Topography of acute stroke in a sample of 439 right brain damaged patients. *Neuroimage Clinical, 10*, 124-128. doi: 10.1016/j.nicl.2015.11.012

Spinazzola, L., Bellan, G., Pia, L., & Berti, A. (2014). Unawareness of Motor and Somatosensory deficits after stroke (UMAS): Validity and Reliability of UMAS Questionnaire. *Applied Psychological Bullettin, 62*(270), 37-58.

Tsakiris, M. (2010). My body in the brain: a neurocognitive model of body-ownership. *Neuropsychologia, 48*(3), 703-712. doi: S0028-3932(09)00390-X [pii] 10.1016/j.neuropsychologia.2009.09.034

Vallar, G., & Ronchi, R. (2009). Somatoparaphrenia: a body delusion. A review of the neuropsychological literature. *Experimental Brain Research, 192*(3), 533-551. doi: 10.1007/s00221-008-1562-y

Vocat, R., Staub, F., Stroppini, T., & Vuilleumier, P. (2010). Anosognosia for hemiplegia: a clinical-anatomical prospective study. *Brain, 133*(12), 3578-3597.

Wilson, B., Cockburn, J., & Halligan, P. W. (1987). *The Behavioural Inattention Test*. Bury St. Edmunds: Thames Valley Test Company.

Zeller, D., Gross, C., Bartsch, A., Johansen-Berg, H., & Classen, J. (2011). Ventral premotor cortex may be required for dynamic changes in the feeling of limb ownership: a lesion study. *Journal of Neuroscience, 31*(13), 4852-4857. doi: 31/13/4852 [pii] 10.1523/JNEUROSCI.5154-10.2011

Zeller, D., Litvak, V., Friston, K. J., & Classen, J. (2015). Sensory processing and the rubber hand illusion--an evoked potentials study. *Journal of Cognitive Neuroscience, 27*(3), 573-582. doi: 10.1162/jocn_a_00705