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Embodying a moving alien hand. An investigation of visuomotor integration processes underlying embodiment in healthy controls and in patients with diagnosis of schizophrenia.

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Abstract

The present thesis addresses the build-up of the senses of agency and ownership in schizophrenia, as a clue to understand the mechanisms of self-awareness in these patients. Based on previous literature highlighting disturbances of sense of agency and impairments in sensorimotor integration, we carried out a series of three studies aimed to explore self-body recognition by capitalizing on a visuomotor body illusion, i.e. the mirror box illusion. This paradigm was useful in order to elicit overt sensations of agency and ownership under condition of illusorily embodiment of a moving alien hand.

In Experiment 1, the effect of temporal congruency between visual (experimenter's hand reflected in the mirror) and the proprioceptive (participant's hand) input on subjective and objective measures (namely, embodiment questionnaire and forearm bisection task) of the illusion was addressed in 36 healthy participants and 29 patients affected by schizophrenia. In healthy participants, sense of agency, sense of ownership and bisection performance modulate in accordance with the extent of visuo-proprioceptive synchrony. By contrast, the sense of agency and bisection performance did not significantly vary across conditions in patients. Such results indicate that impaired sensorimotor processes, as testified by previous work on self-attribution task, may explain the altered modulation of embodiment in the schizophrenia group. We hypothesized that two sensorimotor mechanisms might be implicated, namely a widened visuo-proprioceptive TBW and a disruption of efference-related signals. In order to help disentangling the role of these two mechanisms, the second experiment was designed.

In Experiment 2, participants were asked to perform active *vs.* passive movements, while increasing time-lags between the visual and the proprioceptive input were introduced using a custom-made mirror box setting. A sample of 32 healthy controls and 18 patients with schizophrenia was recruited. Preliminary analyses show an altered modulation of the illusorily sense of ownership in patients, which is mostly accounted for by an enlarged visuo-proprioceptive temporal binding window. This result might indicate that an abnormal integration of afferent signals is strongly involved in the disruption of self-body ownership (intended as the self-identification with a body) in schizophrenia. This conclusion, however, warrants caution given the small size of the patients group.

Finally, Experiment 3 represents an exploratory study to test the hypothesis of abnormal malleability of body representation in schizophrenia derived from the literature on rubber hand illusion in schizophrenia. Based on this assumption, it could be expected that patients are abnormally prone to embody an alien hand positioned at an anatomically implausible distance from the body. In order to address this issue, we first sought to verify to what extent high spatial visuo-proprioceptive discrepancy can inhibit the sense of ownership for a moving alien hand in healthy people. Using the same mirror box setting previously mentioned, we obtained results that are only partially in agreement with the hypothesis, since illusory ownership deems to decreases only at the subjective, but not objective level. Further work, using a different experimental manipulation, might better address whether these results

may be due to the task used or to the higher sensitivity of subjective assessment of body ownership to this kind of manipulation.

In conclusion, the present work demonstrates that putatively impaired visuo-motor integration processes in schizophrenia do not only impact on the sense of agency, but also on the recognition of one's own body. These findings expand previous work based on the rubber hand illusion, providing empirical evidence of the fact that disturbances of body perception in schizophrenia can be dependent on defective sensorimotor processes for action.

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1 Self-disturbances in schizophrenia

The awareness of being the agent of own actions is immediately and effortlessly given to us. Such a fundamental component of self-experience may be dramatically undermined in schizophrenia, resulting for instance in the pathological belief of being in control of other people or entities. The present chapter will review experimental accounts about disturbances of self-agency in schizophrenia.

1.1 Self-reference and schizophrenia

For a long time, schizophrenia has been characterized as a disorder of the Self. Common ideas encompassing several formulations of core psychopathology of this syndrome regard the disintegration of the Self and the loss of the synthetic capacity of the psyche to hold together self-components into an unitary "I" experience (Mishara, Lysaker, & Schwartz, 2014). In fact, many symptoms suggest a disconnection of the Self from the patient's experience that insidiously impinges on the first-person access to the representation of one's own actions, thoughts and perceptions. For instance, schizophrenic patients may report that alien thoughts come into their mind and they may develop the delusional conviction that those thoughts originate from someone or something else (Henriksen, Parnas, & Zahavi, 2019). Similarly, they may hear voices without a veridical stimulus (Allen, Larøi, McGuire, & Aleman, 2008) or while they are actually sub-vocally speaking (C. Frith, 2005).

Self-reference involves the arising of two fundamental sensations towards the object of ongoing experience, i.e., *sense of ownership* and *sense of agency*. The sense of ownership pertains to the feeling that an experiential content belongs to us, while the sense of agency is the feeling of causation over it. As Gallagher elucidated, one may typically feel sense of ownership and sense of agency for a movement, but they would do so likewise for a thought, a feeling, etc (Gallagher, 2000). In the studies reported in the current thesis, these aspects of self-experience are addressed in healthy people and patients with schizophrenia, while they perform a movement, in order to further clarify the emergence and variability of their sense of agency and sense of ownership over a moving hand.

1.2 Sense of agency in schizophrenia

The term '*sense of agency*' is variously used to refer to several aspects of the subjective experience of performing an act, such as the feeling of being the wilful initiator of an action (Gallagher, 2000), the sense of intending and executing an action (Tsakiris & Haggard, 2005a), the feeling of being in control of our own actions and the sense of authorship over their consequences (Moore, 2016).

Although it permeates our experiential life, an explicit sense of agency is usually minimal and "phenomenally thin", i.e., we are hardly aware we are acting upon the world (Haggard, 2017). A recent model tries to capture the different facets of agency phenomenology drawing the distinction between the *feeling of agency* and the *judgment of agency*. The feeling of agency is the non-conceptual and implicit feeling of being the author of our own actions. This feeling is based on a stable perception-based representation of agency arising from the processing of sensorimotor signals. The content of this representation allows the classification of an action as self-caused or not self-caused, but it manifests as a non-analyzable whole. The judgement of agency, on the other hand, is the conceptual and explicit belief-like awareness of being the agent. The judgment is dependent on a conceptual representation of agency which is formed by inference from the proper weighting of different non-sensorimotor cues, e.g., situational cues, like the presence of other agents in a room ("*I may believe I am the agent of the action just because I take into account the fact I am alone in the room*"; Synofzik, Vosgerau, & Newen, 2008a, p. 8). The content of this representation has instead an object-property structure (Synofzik, Vosgerau, & Newen, 2008b).

The sense of agency represents a core component of Self-reference as it implies the Self as the agent of actions or thoughts (Gallagher, 2000). Neural processes allowing such a basic sense of "*mineness*" might be dramatically undermined in schizophrenia. This notion becomes apparent in the contribution by Kurt Schneider who, looking for schizophrenic diagnostic specificity, grouped together a set of ego-related symptoms (the first-rank symptoms) that can be regarded as the expression of a pathological break-down of self-agency ascription processes[1]. Common denominators of first-rank symptoms are the difficulty to disentangle who is the agent (the Self or the non-Self) and the feeling of being influenced by the external environment (sense of passivity). Patients suffering from these symptoms may manifest the sense of lack of control over feelings and actions, developing then the belief of being at the mercy of external agents or forces (Bürgy, 2011; Mishara et al., 2014). Experiences

[1] It is worthy of note that a reduced sense of agency is not a unique quality of the schizophrenic syndrome. The anarchic hand syndrome, for instance, is a neurological syndrome manifesting as a "limb-specific" disruption of sense of agency (Braun et al., 2018) in which the hand starts to act independently from patient's will, as though an autonomous entity. Agency disruptions characterizing schizophrenia and the anarchic hand syndrome are similar, meaning that both reflect the lack of control upon movements. Nonetheless, their phenomenology differs because patients suffering from the anarchic hand complaint the hand is misbehaving, and they may try to stop it, but they do not report that an external agent/force is actually guiding their own actions (C. Frith, 2005).

Schneiderian first-rank symptoms	
Auditory hallucinations	
• **Audible thoughts**	Hearing voices uttering one's own thoughts aloud (also thought echo).
• **Third-person hallucinations**	Hearing two or more voices arguing about one in the third person.
• **Running commentary**	Hearing a commentary on one's own actions as they occur.
Altered somatic perceptions	
• **Somatic passivity**	The experience of being a passive and reluctant recipient of bodily sensations imposed by external agents (it may be due to haptic, thermic or kinaesthetic hallucinations or triggered by real stimuli).
Altered thought experience	
• **Thought withdrawal**	The experience that external agent removes one's own thoughts from his/her head.
• **Thought insertion**	The experience that external force imposes alien thoughts upon his/her passive mind.
• **Thought diffusion**	The experience that one's own thoughts are no longer confined into one's own mind and they become audible in the external world. Broadcasting is the usual secondary delusional explanation (eg., telepathy, television…).
Altered experience of feelings and will	
• **Made feelings**	Experiencing feelings that lose their special note of mineness and are attributed to external sources.
• **Made impulses**	Experiencing powerful drives imposed by external force to carry out certain actions.
• **Made volitional act**	Experiencing own actions as being under control of external influence. The individual feels he/she is an automaton, a passive observer of his/her own actions.
• **Delusional perception**	Elaborating a real percept in a delusional way.

Table 1. Schneider's first rank symptoms. *Traditionally called "Ich-Störungen", they refer to the experience of one's thoughts, actions, feelings and bodily sensations being 'made', influenced or manipulated by other agents.*

of passivity can affect different aspects of self-experience, such as the sense of control over own actions, but also the sense of ownership of self-produced thoughts, perceptions and feelings (Crow, 1997; Mellor, 1970) (Table 1). For example, patients can experience sensations of alien control over movements, e.g., motor passivity: "*I'm forced to walk around. I'm being made to turn right and left*" (Waters & Badcock, 2010). Likewise, they can vividly perceive one or more commanding voices, usually belonging to external entities, that are able to exert physical and emotional influence on them in an authoritative and unpredictable manner, e.g., blaming voices: "*Ha ha, you deserved it because you brought all this pain and suffering.*" (Upthegrove et al., 2016; p. 93)

In the past decades, a substantial body of research has addressed schizophrenia as a pathology of the sense of agency. An influential hypothesis posits that passivity symptoms stem from an impairment affecting central mechanisms for monitoring and rapid correction of actions (Feinberg, 1978; C. Frith, 2012; C. D. Frith, Blakemore, & Wolpert, 2000). This hypothesis based on the assumption that any time a voluntary motor command is issued to the musculoskeletal system, a prediction of sensory feedback is derived from an efference copy of the motor command. Put differently, the motor control system predicts all the perceptual changes caused by the execution of an intended movement. Predictions[2] and outcomes of a voluntary action are systematically compared by a specialized structure in a way that whenever they differ, a prediction error is computed and employed for motor correction (Wolpert & Ghahramani, 2000). This theoretical framework is usually referred to as *the comparator model*. Crucially, the comparator has been also regarded as a central mechanism underpinning self-experience, that one allowing the perceptual distinction between sensory events that occur as a result of one's own actions and events that occur as the result of someone else's actions. This would be possible by the *sensory attenuation* of the perception of self-applied stimuli (Sarah J. Blakemore, Frith, & Wolpert, 1999; Sarah J. Blakemore, Wolpert, & Frith, 1998). Hence, whenever a sensory event corresponds to the predicted consequence of a willed action, the result of the comparison between prediction and outcome will be zero (i.e., any prediction error at the output of the comparator). Accordingly, sensations produced by one's own movements are labelled as self-generated. This would allow to unequivocally attribute self-produced sensations to our own agency, and so to distinguish between self-produced *vs.* externally produced actions.

According to Frith, the delusional feeling of alien control is the product of a dysfunctional forward modeling, that is a problem affecting the efferent copy of the motor command (C. Frith, 2005). Because predictions of outcome are not appropriate, sensory feedback deriving from one's own actions cannot be cancelled out by a proper internal prediction and are thus perceived as vivid as externally-produced sensory events. This would account for delusions of control, such as the feeling that thoughts and actions are transmitted or driven by external agents. The finding that patients with a current delusion of control did not show the attenuation of self-touch perception when asked to judge the ticklishness of internally- *vs.* externally- generated tactile stimuli supports this assertion, suggesting in particular a deficit affecting the forward outcome model (Blakemore, Smith, Steel, Johnstone, & Frith, 2000). Frith suggests that the overactivation of parietal areas (Spence et al., 1997) may represent a neural correlate of the failure of sensory attenuation in delusions of control (Frith et al., 2000). Comparing schizophrenic patients with and without passivity symptoms during the performance of free *vs.* stereotyped joystick movements, Spence et al. (1997) found that the current presence of passivity symptoms is associated to the hyperactivation of the right inferior parietal lobule and cingulate gyrus. Interestingly, this overactivation was found to be reduced after remission of symptoms.

The overestimation of a force shown by healthy individuals when asked to perform the force-matching task also proves abnormalities affecting sensory attenuation. In the study of Shergill, Samson, Bays, Frith, & Wolpert (2005) participants were asked to perceive a target force applied on their left finger by a motor torque and to reproduce this force, either by pushing with their right index on the motor torque (direct estimation) or by using a joystick controlling the motor torque (indirect estimation).

[2] Predictions (also called forward models) can regard the trajectory of the moving body part in time and space (*the forward dynamic model*) or the kinematic and sensory feedback that the movement will produce (*the forward output model*).

Critically, only when the participant is required to match the force just experienced through direct estimation, mechanisms for sensory attenuation are recruited. This fact makes healthy participants overestimate the target force given that the sensory outcome of their pushing movement is predicted and thereby partially cancelled out. In line with the proposal of a defect in the prediction processes, participants with schizophrenia demonstrated instead to be more accurate than controls in reproducing the target force via direct estimation (percentage of attenuation: 27.5% in the patient group *vs.* 43.5% of the control group) because the cancellation process does not properly operate.

Frith's hypothesis has been also addressed by smooth pursuit eye-movements performance[3]. In Lindner et al.'s study, participants looked at a fixation target moving rightward amidst a cloud of white dots serving as background. After each trial, they were asked to report the direction of the perceived background motion. The speed of the background was varied according to a staircase procedure until the background resulted perceptually stable (*Point of Subjective Stationarity*: 50% leftward and 50% rightward answers). By subtracting the background velocity at the point of subjective stationarity (i.e., measure of the predicted amount of retinal image motion induced by eye rotation) from the velocity of the pursuit eye-movement (i.e., a measure of the actual amount of retinal image motion), Lindner and colleagues could quantify the size of the "compensated reafference", CR. As demonstrated by their regression analysis, the "CR deviation" (i.e., a measure of the absolute deviation of individual CR from the average CR of the control group) was specifically positively correlated with the severity of delusions of influence. This result, which suggests a suboptimal compensation of the retinal reafference in patients with delusions of influence, provided additional evidence for the claim that passivity experiences might be due to comparator model deficits (Lindner, Thier, Kircher, Haarmeier, & Leube, 2005).

Notwithstanding, several studies undertook within the theoretical framework by Marc Jeannerod and coworkers disproved the hypothesis of an impairment of prediction in schizophrenia (Daprati et al., 1997; P. Fourneret, Franck, Slachevsky, & Jeannerod, 2001; Pierre Fourneret et al., 2002; Franck et al., 2001). Jeannerod proposed that we may distinguish between the covert and the overt stage of action that, far from being completely dissociated processes, constitute two counterparts of the same phenomenon, i.e., *the representation-execution continuum* (Georgieff & Jeannerod, 1998). An example of covert action is appraising the feasibility of a movement because it implies motor imagery, namely the mental simulation of the posture to accomplish the required estimation. The existence of these two modalities of action is supported by partially non-overlapping neural areas (Jeannerod, 2001). Additionally, Jeannerod distinguished between conscious and unconscious

[3] The visual system can distinguish between movements on the retina that are due to movements in the world from those due to our own movements. The comparator is here assumed to contrast the retinal feedback with the visual prediction both to calculate the prediction error so to correct eye-movement, but also to remove the amount of motion in the retinal feedback that has been produced by one's own eye movement (i.e., visual feedback attenuation): In this way the retinal image slip of the surrounding environment induced by eye rotation can be self-attributed and the environment appears stationary.

processes underlying self-attribution of actions. In principle, comparator-like comparisons between efference and reafference can occur at both unconscious and conscious level. On the "sub-personal" level, effortless and automatic comparisons provide information for the implicit self-identification (these mechanisms are those recruited for the online monitoring and correction of self-generated movements). On the "personal" level, effortful and conscious comparisons of signals provide information about the goal of the action and the agent of the action itself. In this regard, sense of agency disorders of people with schizophrenia are due to the unproper functioning of the representational level of action (Pierre Fourneret et al., 2002; Jeannerod, 2009).

A first line of experiments by Jeannerod's group addressed the ability of agency judgement in schizophrenia. These experiments were designed in order to provide participant with movements of uncertain origin, meaning that the agent of the movement could be the participant himself or an external agent (e.g. an experimenter). Under this condition, the participant was to make conscious agency judgements (Georgieff & Jeannerod, 1998; Jeannerod, 2009). Basically, action recognition was dependent on the ability to detect fine-to-gross spatiotemporal deviations introduced in the visual feedback of a performed movement.

In Daprati et al. (1997), the visual feedback of the hand movement was provided through a video-screen. The video consisted in (1) participant's own hand moving, (2) the experimenter's hand performing the same gesture, or (3) the experimenter's hand performing a different gesture. Participants were asked to verbally judge whether the hand in the screen was their own. In the more ambiguous condition (the second one), delusional and hallucinating patients significantly underperform with respect to healthy participants (error rate: delusional=80%, hallucinating=77%, controls=30%). By using a more sophisticated technique, Franck et al. (2001) reached analogous results. Participants were required to judge whether a virtual hand, visually overlying their own hand, exactly replicated their actual own movement while angular bias or temporal delays were systematically added to the movements of the virtual hand. Overall, patients made errors up to higher degrees of feedback distortion. Besides, results showed that the subgroup of patients with delusions of influence were specifically less sensitive to angular deviations compared to the other groups. Taken together, this couple of studies consistently shows a significantly higher tendency by patients to misinterpret others' movements as their own movements (i.e., *hyper-attribution of self-agency*) because of a higher mismatch detection threshold. The proneness for over-attribution error in schizophrenia in fact reveals a worsening of an error tendency yet observed in healthy controls. In general, deficiency in the comparator could hardly explain both the hypo-attribution of self-agency characterizing passivity symptoms and the over-attribution of self-agency experimentally observed in these studies (Georgieff & Jeannerod, 1998). Franck et al. (2001), for instance, commented that an effective understanding of spatial cues of a movement (e.g., direction of the motion trajectory) is crucial to grasp the goal of the action and agent's intentions during the observation of others' movement. The incapability to understand motor spatial cues leads to confuse who is the agent of an observed action. The misinterpretation manifests as the tendency to believe of being the agent of the movement performed by others with the parallel feeling of being controlled by them. As Franck seems to suggest, the impairment affecting representations serving the observation of action motivates the failure to detect gross spatial mismatch between reafferent feedbacks in influenced patients.

A couple of studies by Fourneret more straightforwardly called into question the hypothesis that comparative mechanisms go wrong in schizophrenia. Based on the notion of the presence of unconscious to conscious levels of motor processing, he addressed the conscious access to motor corrections by adopting a visuomotor adjustment task ("*the action conflict task*"). Subjects were simply to trace a line in the sagittal direction up to a visual target. However, they were precluded from viewing their hand, they could only see the drawn line reproduced by a dedicated system above their hand movements. The line, however, was systematically rotated by some degrees to the right via a computer. Participants have to become aware of the intersensory mismatch and begin consciously compensating the visuomotor conflict by predictively rectifying the hand trajectory to be effective in carrying out the task (Fourneret et al., 2001; Fourneret et al., 2002). By presenting a constant deviation of 15° in the feedback, patients with schizophrenia performed as well as healthy controls, even though almost half of them did not declare to have switched to the conscious compensation at some point. The presence of Schneiderian symptoms was not a special feature of patients without awareness of the active compensation (Fourneret et al., 2001). By gradually increasing the bias in the visual feedback (from 0° to 20°), patients performed as good as controls at smaller deviations, but they got worse when larger deviations were presented. That is, patients were over-reliant on the biased visual feedback while healthy participants paid greater attention to proprioceptive information to carry out the trajectory adjustment. In addition, patients showed a poor sense of the actual trajectory of their hand when asked to judge their hand trajectory with respect to an abacus with several lines of different angular deviation (Fourneret et al., 2002). As Fourneret and colleagues argued, the preserved ability to compensate smaller discrepancies accounts for unimpaired automatic comparative mechanism, against Frith's hypothesis. Conversely, the problem would stay in the switch to the conscious modality of compensation: The abacus test suggests that the lack of a reliable access to the conscious hand representation make patients poorly aware of the actual position of their hand when they are to intentionally recalibrate the movement trajectory to compensate for larger incongruencies. As such, authors supposed a passivity experience in their schizophrenic patients, i.e., they might have felt the visual feedback was gradually pulled away from their motor intentions and plans and they "*may have monitored the resistance exerted by this external force against the effort that they said they felt to move in the desired direction*" (Fourneret et al., 2002; p. 153).

As such, studies presented so far show a rather inconsistent scenario. On the one hand, the hypo-attribution of self-agency characterizing passivity symptoms can be explained by an altered sensory attenuation. This result supports the notion of defective comparative mechanisms. On the other hand, the hyper-attribution of self-agency and the reduced visuomotor adjustment disprove comparator model hypothesis in favor of a disruption of conscious processes for action (Synofzik, Thier, Leube, Schlotterbeck, & Lindner, 2010). Synofzik and colleagues proposed that the reason for the seeming incompatibility between hypothesis based on the comparator model and the increased mismatch detection threshold shown by people with schizophrenia may rely on the extremely high variability affecting internal signals (Synofzik et al., 2010). To test this hypothesis, they designed a visuomotor adaptation task aimed at quantifying the variability of motor predictions and proprioceptive input (i.e., internal signals) in schizophrenia. Visuomotor adaptation was induced by a virtual hand providing a distorted feedback of pointing movements performed by subjects. The distortion consisted in the virtual hand gradually rotates 6° clockwise with respect to the veridical movement direction. Throughout the adaptation procedure, the movement was performed with the visual feedback provided (*feedback trials*) and without it (*perceptual probe trials*). At the end of both kind of trials, participants were asked to give a perceptual estimate of the direction of the pointing just performed. Crucially, the perceptual estimate performed during perceptual probe trials aimed at probing the degree of adaptation of internal signals to the distorted visual feedback previously seen. At both feedback and perceptual probe trials, perceptual estimates of schizophrenia group showed a significantly larger trial-by-trial variability. Moreover, the extent of trial-by-trial variability at perceptual probe trials positively correlated with the severity of delusions of influence. Therefore, patients display extremely imprecise (thus unreliable) predictive and proprioceptive signals, mainly in case of passivity symptoms. Besides, the extent of adaptation of the perceptual estimates to the rotated virtual hand in feedback trials (not in perceptual probe trials) was almost two-time larger in patients. This finding suggested that the disruption of internal cues for sense of self-agency (as shown by results above) may prompt perceptual system of patients to add much more weight to exteroceptive signals (e.g., visual feedback) when present[4]. In the light of these results, authors finally speculated that in case external cues are temporarily not attended or unavailable, and agency attribution can thereby only be driven by internal cues and predictions, patients might additively assume that external forces are causing or influencing their actions. Additionally, they suggested that agency disturbances in schizophrenia are mostly related to predictive mechanisms serving motor perception instead of those serving motor execution. In fact, at some trials during the experiment participants were to pinpoint toward a visual target without the virtual feedback (*motor probe trials*). These trials aimed at targeting processes for visuo-motor adjustment, that is prediction

[4] This interpretation was conceived within the conceptual framework of the Multifactorial Weighting Model that stresses the weighted integration of many cues of self-agency. According to this model, the brain is constantly weighting perceptual (interoceptive and exteroceptive signals along with internal predictions) and cognitive cues of sense of agency on the basis of their respective reliability in a given situation (Synofzik et al., 2008b, 2008a).

error calculation and error correction. At these trials, performance of patients was in fact comparable to that of healthy controls.

Sense of agency disturbances in schizophrenia have been also addressed by the experimental paradigm devised by Patrick Haggard. This procedure provides a viable way to probe a specific phenomenon characterizing time-awareness of action, the *intentional binding*. The experimental task requires participants to press a key that triggers a tone and to make time judgements for actions by referring to a rotating clock. In the experimental conditions, participants are to report either the time when they press the key or when they heard the tone. In two additional baseline conditions, they perform the same time estimations, but the key press and tone occur in isolation. When participants can develop a sense of causation over the tone (during the experimental conditions), they perceive voluntary key press as occurring later and their auditory sensory consequences as occurring earlier than the actual timing. In other words, action and tone are perceptually shifted closer in time as though the action was attracted by its external consequence. This effect reveals that there exist certain processes that integrates the conscious representation actions and event which lead to a distortion of time-awareness of action (Tsakiris & Haggard, 2005a). Intentional binding effect may hence represent the measurable consequence of the fact that "*the core of sense of agency is the association between a voluntary action and an outcome*" (Haggard, 2017, p. 198) and it can thereby be used as an implicit marker of sense of agency.

Participants with schizophrenia demonstrated a stronger intentional binding effect because they showed to underestimate the time interval between the action and the sound more strongly than healthy controls (51 milliseconds *vs.* 229 milliseconds). The hyper-binding effect suggested that patients have an exaggerated association between the representation of the action and of its outcome, an effect that might also account for the more tolerant temporal binding window and for the hyper-attribution of self-agency found in previous studies (Haggard, Martin, Taylor-Clarke, Jeannerod, & Franck, 2003).

The comparator model implies that agentive awareness of action is a "*post-action verificational judgment*"[5] (Tsakiris & Haggard, 2005; p. 391), in which any contribution coming from preparatory processes like the intention-to-move is at stake, e.g., the brain infers the agent only when the tone has occurred, uniquely adopting a retrospective reconstruction of agency. Such a view has been partially disproven by Tsakiris & Haggard (2003) since they provided evidence that the agentive awareness of action also depends on the generation of the motor intention and on predictive signals, both processes operating prior to any perceptual feedback generation. In view of these considerations, Voss and colleagues examined the distinctive role of prospective and retrospective mechanisms to agency attribution in schizophrenia. Participants underwent two experimental conditions where the key press

[5] The comparator model postulates that sense of agency arises after the comparison between the sensory feedback and the prediction. Accordingly, sense of self-agency is a post-hoc judgment largely dependent on the time the motor reafference reaches the comparator (Gallagher, 2000). Conversely, any role is attributed to sensorimotor mechanisms at an earlier stage in the planning of action.

caused the tone to occur on 50% and 75% of the total trials: This make the generation of prediction about the occurrence of the tone less and more likely. The strength of intentional binding across conditions revealed that healthy people present a larger predictive than retrospective component, whereas the opposite pattern was true for patients with schizophrenia. This result, which highlighted the overreliance of patients on postdictive agency attribution processes, suggested that sense of agency is mostly inferred retrospectively starting from the happening of the sensory event and independently from its prior probability. The authors argued that "*the patients appeared to experience the linkage between action and tone as a surprising contingency discovered anew each time it occurred*" (Voss et al., 2010; p. 3110) because in schizophrenia "*the brain may be in a constant state of surprise, attempting to understand the events that it has itself generated*" (Haggard, 2017; p. 205). Furthermore, the lack of predictive shift of action awareness was correlated with severity of delusions and hallucinations.

In general, abnormal performance in self-agency ascription in schizophrenic persons has been regularly reported in all studies summarized above. Sensorimotor mechanisms underlying the impairment has been targeted from different perspective by different self-attribution tasks, both on implicit and explicit ground. A summary of the main results is here attempted.

Studies based on the *sensory attenuation effect*

Sensory attenuation constitutes the perceptual bias associated to the prediction error resulting from the subtraction operated between actual and predicted sensations engendered by a voluntary movement. The reduction of sensory attenuation of predictable stimuli (e.g., self-applied touch) observed in schizophrenic population might depend on the fact that inadequate internal predictions and/or impaired comparative mechanisms impede that sensory consequences of action to be partially removed from perception (S. J. Blakemore et al., 2000; Lindner et al., 2005; Shergill et al., 2005). As self-produced stimuli are perceived as vivid as externally-generated ones, this experimental result could account for the phenomenology of passivity (ipo-attribution of self-agency, sense of external control). Findings based on sensory attenuation have been proposed to reflect a compelling evidence of a deficient implementation of the comparator system in delusions of control given that sensory attenuation represents the output of the comparison (Lindner et al., 2005). Generally, this line of evidence suggests that the cause for delusions of influence relies on prediction error calculation in its function to tag sensory feedbacks as "mine".

Studies based on the *intentional binding effect*

The intentional binding effect provides another indirect measurement of agency. It reveals the distortion of time characterizing the cognitive representation about an intended act and its outcomes. The intentional binding in people with schizophrenia was found to be largely driven by the retrospective component agency, namely by the occurrence of the sensory consequence of the action (Voss et al., 2010). This fact, accounting for the abolishment of the prospective component of agency, may overall agree with the above-mentioned hypothesis of defective internal prediction as functional substrate for schizophrenic passivity (Haggard, 2017).

Studies based on the *visuo-proprioceptive mismatch detection*

This ability consists in the conscious detection of a cross-modal error between feedback. People with schizophrenia tend to self-attribute movements at higher degrees of visual feedback perturbation (Daprati et al., 1997; Franck et al., 2001), a result broadly indicating a more tolerant detection threshold for mismatches between visual and proprioceptive signals.

Studies based on the *visuomotor recalibration* of perceptual estimates and motor trajectory

Visuomotor recalibration is thought to depend on the processes of error correction, since it is assumed that once the visuo-proprioceptive mismatch is detected, the computed error is used to update the internal predictions of sensory consequences (*visuomotor adaptation task*, see above) and/or to correct the motor command (*visuomotor adjustment task*, see above). Individuals with schizophrenia showed (a) to be poorly aware of performing visuomotor mismatch adjustments (Fourneret et al., 2001), (b) to be poorly able to implement a conscious adjustment of visuo-proprioceptive mismatches because of scarce proprioceptive awareness (Fourneret et al., 2002) and (c) to have a larger adaptation of perceptual estimates to distorted visual feedback (Synofzik et al., 2010). Overall, these findings agree with a general overweight of visual feedback at the detriment of proprioception and sensory predictions during the integration of movement-related signals.

Partially consistent results might suggest that both the generation of motor prediction and comparative mechanisms between afferent feedbacks are involved in sense of agency disorders in schizophrenia. Apart from tentative general conclusions, actual causes for agency-related symptoms turns out far from clear.

2 Body representation in schizophrenia

A neuropsychological tool for the investigation of bodily awareness is the induction of bodily illusions. Body ownership illusions (BOIs) can be classified in two major categories: visuo-tactile and visuo-motor illusions. As concerns schizophrenia, experimental evidence on bodily awareness and the sense of body ownership mainly comes from the former type of illusion. In the current chapter, a summary of available studies will be provided, along with a brief introduction on bodily illusions and their subtypes.

2.1 BOIs and their correlates

One of the most powerful method to address bodily awareness is the induction of a BOI. The core aspect of them is the elicitation of the illusory feeling that an external body (e.g., a virtual body) or an external body part (e.g., a mannequin's hand) belongs to us.

A paradigmatic example of these illusions is the Rubber Hand Illusion (RHI) first discovered by Botvinick and Cohen in the 1998 (Botvinick & Cohen, 1998). The classic experimental protocol provides that the person looks at a fake hand placed in bodily alignment with his/her actual hand hidden behind an opaque screen. When both hands are touched simultaneously and on homologous areas, the person usually reports that the fake hand seems to be a part of their body and that she gets the feeling the tactile stimuli she perceives on her hand are located on the fake hand.

Body awareness is thought to be intrinsically multimodal in nature. Body illusions like the RHI demonstrate the importance of the integration of the plurality of somatic signals for body processing (Azanõn et al., 2016). Overall, the content of body awareness hinges on:

- *afferent exteroceptive signals* (e.g., visual, tactile and nociceptive feedback)
- *afferent interoceptive signals* (e.g., proprioceptive, vestibular, homeostatic signals)
- *efferent "endogenous" signals* (e.g., predictions of sensory consequences of action, anticipation of sensory stimuli)

After the seminal work of Cohen and Botvinick, many bodily illusions have been introduced in the experimental research hitherto. Kilteni and colleagues (Kilteni, Maselli, Kording, & Slater, 2015) have recently outlined a comprehensive account of BOIs. They distinguish BOIs according to the different multimodal stimulation they can be triggered by, namely

- visuo-tactile BOIs – eg. the classical RHI (Botvinick & Cohen, 1998)
- visuo-motor BOIs – eg. the moving RHI (Kalckert & Ehrsson, 2012)
- visuo-proprioceptive BOIs – eg. the visuo-proprioceptive RHI (Giummarra, Georgiou-Karistianis, Nicholls, Gibson, & Bradshaw, 2010)
- tactile-proprioceptive BOIs – eg. the somatic RHI (Ehrsson, Holmes, & Passingham, 2005)

Therefore, BOIs can arise from the combination of afferent information from heterogeneous sensory channels. Apart from the nature of multisensory signals involved, BOIs are governed by some principles that rule and constrain the integration of the multimodal information available to the brain at a specific time. Key requirements to meet for BOI elicitation are

- *temporal congruence*: the temporal correlation of multisensory information;
- *spatial congruence*: the spatial coincidence of multisensory information;
- *anatomical plausibility*: the plausible alignment of the external body part with the rest of the body of the subject;
- *shape congruence*: the shape similarity of the external object and the real counterpart

Synchrony between multisensory feedback certainly plays a pivotal role in BOIs. For instance, it is consistent finding that asynchronous stimulation abolishes the RHI. In this regard, a technical study revealed that temporal delays shorter than 300 milliseconds between visual and tactile stimuli are required for the classical RHI to arise (Shimada, Fukuda, & Hiraki, 2009). As concerns the visuomotor variant of the RHI, the illusion is strongly attenuated at time windows larger than 200 milliseconds (Ismail & Shimada, 2016). Another important aspect of BOIs is the positioning of the artificial hand, which should be in plausible anatomical alignment with human joints articulations. Indeed, when the rubber hand is rotated by 180° with respect to the actual hand the ownership illusion does not usually come up despite multisensory temporal correlations (Kalckert & Ehrsson, 2012). This latter kind of manipulation interestingly indicates that BOIs do not only emerge in a reactive way, purely produced by bottom-up mechanisms, but they are also shaped by the biophysical constraints of the human body as a result of top-down influences coming from general body scheme representations (Tsakiris & Haggard, 2005b).

General consensus is that BOIs are mediated by multisensory integration mechanisms pertaining to the representation of peri-hand and peri-personal space, i.e., the portion of space immediately adjacent the hand and the body that is thought to be functional to guide action towards objects (*reaching space*) and to the planning of defensive reactions (*defensive space*) (Macaluso & Maravita, 2010; Makin, Holmes, & Ehrsson, 2008; Noel, Blanke, & Serino, 2018). According to Makin and colleagues view, the RHI arises as follows. First, the vision of a dummy hand in an anatomically plausible position, which is by itself able to induce the visual capture of positional cues[6], causes the space around the dummy hand to be represented as peri-hand space. Second, the remapping of the space around the dummy hand in peri-hand coordinates triggers multisensory integration mechanisms typically pertaining to peri-hand space, that is the binding of stimuli from different sensory channel in a unified multimodal percept. This latter phenomenon would be responsible for illusory sensations like localizing the felt touch onto the rubber hand, the referral of touch (Makin et al., 2008).

2.2 Sense of ownership in schizophrenia

The totality of the studies that addressed bodily awareness and the sense of ownership in schizophrenia (Ferri et al., 2014; Graham, Martin-Iverson, Holmes, Jablensky, & Waters, 2014; Peled, Pressman, Geva, & Modai, 2003; Peled, Ritsner, Hirschmann, Geva, & Modai, 2000; Thakkar, Nichols, McIntosh, & Park, 2011) have used visuo-tactile versions of the RHI (Table 2).

Peled and co-workers first conducted a couple of RHI studies on patients with schizophrenia (Peled et al., 2003, 2000). These studies first found that the RHI is experienced more vividly and has an earlier onset in schizophrenia population (Peled et al., 2003, 2000). Interestingly, they also observed a positive correlation between questionnaire items about ownership sensations and the severity of hallucinations (Peled et al., 2000). The authors propose that the higher susceptibility of patients depends on the spurious reconciliation of sensory feedbacks within multimodal brain regions, as supported by the abnormal pattern of modulation of evoked potentials detected in associative higher-order parietal scalp areas (Peled et al., 2003).

Likewise, Thakkar et al. (2011) found that patients report higher intensities of ownership for the fake hand than controls after both synchronous and asynchronous visuo-tactile stimulation. Furthermore, patients showed an enhanced proprioceptive drift after synchronous stimulation, suggesting stronger visual capture of proprioceptive feedback in schizophrenia. In line with the study above, positive correlations were found between the vividness of the RHI during the synchronous condition and severity of positive symptoms (hallucinations, delusions of controls and delusions of reference) but, a negative correlation with somatic delusions. Authors argued that patients' self-reports of strong RHI even under condition of asynchronous stimulation may be indicative of a coarser time window of visuo-tactile integration affecting bottom-up processes of multisensory integration. Beyond

[6] As for the computation of hand position, visual capture of proprioception refers to the overweighting of visual feedback to the detriment of proprioceptive signals. In the RHI, this results in the central hand representation spatially shifted towards the fake hand.

	procedure	self-report	objective correlates
Peled et al., 2000	classical RHI	• the illusion is more intense in SZ than HC • the illusion arises faster in SZ than HC	–
Peled et al., 2003	classical RHI	• the illusion is more intense in SZ than HC • the illusion arises faster in SZ than HC	• late EEG potentials evoked by touch stimuli administered during the illusion in P4-C4 are smaller than potentials evoked by stimuli delivered before the illusion in SZ; the opposite pattern is true for healthy controls
Thakkar et al., 2011	classical RHI	• the illusion is more intense in SZ than HC, irrespective of the synchrony of the stimuli	• the proprioceptive drift is larger after synchronous stimulation in SZ than HC • as in HC, temperature drops in the right stimulated hand and increases in left unstimulated hand in SZ
Graham et al., 2014	projected-hand illusion	• the illusion does not decrease in the asynchronous condition in patients with current symptoms of passivity as compared to HC and other schizophrenia groups	–
Ferri et al., 2014	anticipation-based RHI	• the illusion dependent on anticipation processes is less intense in SZ than HC	–

Table 2. Overview table of RHI studies in schizophrenia.

that, the general increased susceptibility to the illusion would be dependent on significantly weak and flexible internal top-down representations of the body.

Starting from the hypothesis that self-disturbances in schizophrenia do not uniquely rely on altered sense of agency, but they are also related to body representations distortions, especially for patients suffering from passivity, Graham et al. (2014) submitted a digital video version of the RHI to three clinical subgroups (i.e., “current”, “past”, “never” passivity symptoms). Sensations of loss of agency over one’s own hand were enhanced in all the clinical subgroups (regardless of the synchrony of stimulation) relative to healthy controls, pointing to hypo-agency as a common trait of individuals with schizophrenia. By contrast, they found “current” or “past” passivity subgroups to show higher level of disembodiment over their own real hand irrespective of the synchrony of stimulation; the same subgroups demonstrated lower accuracy at the most difficult trials of the hand laterality task. As the authors proposed, these latter findings suggest body image and body schema distortions in individuals with passivity symptom profile. Lastly, they observed that only the current passivity symptoms subgroup failed to show the usual decrease of sense of ownership and sense of agency for the projected-hand in the asynchronous compared to the synchronous condition, indicating that an enlarged temporal binding window may be involved in the onset and persistence of the experiences of passivity in patients.

Lastly, a study carried out by Ferri et al. (2014) employing an edited version of the RHI where tactile stimuli approach but do not touch the participant’s hand. Inducing tactile expectations only, which is an effective method to elicit the illusion in healthy people, means to elicit visuo-tactile integration processes by prediction processes instead of by actual stimuli. Patients experienced the illusion of ownership over the rubber hand to a lesser extent than the control group. Additionally, the intensity of the illusion experienced by patients was here positively correlated with the severity of anhedonia (the capacity to experience pleasure in relation to intellectual, social and perceptual stimulation). Overall, results were interpreted as the consequence of altered anticipation of touch in schizophrenia, a fact that might accounts for insufficient predictive mechanisms of action.

Altogether, these studies point to altered visuo-proprioceptive-tactile integration and/or disordered pre-existing body representations (Klaver & Dijkerman, 2016). The enhancement of the RHI, which is suggestive of abnormally malleable body boundaries, may be of remarkable interest from the perspective of selfhood disturbances in schizophrenia. Overall, it can be noticed a relation between symptoms related to self-disturbances and RHI in almost all studies. Studies adopting the classic procedure found a positive relation between the RHI intensity and the severity of positive symptoms, like hallucination and delusion of control (Peled et al., 2003, 2000; Thakkar et al., 2011), whereas the last study focusing on anticipation mechanisms found the RHI intensity to be positively related to anhedonia (Ferri et al., 2014). Productive symptoms like delusion of external controls have long been regarded as outcomes of ego-disturbances: they are characteristic of the acute psychotic phase and they are particularly crucial for the diagnosis of schizophrenia (see 1.2, first-rank symptoms). On the other hand, a more recent reconceptualization of the schizophrenia put forward within the phenomenological approach to psychopathology has brought to the fore disembodiment, which consists in a diminishment of the basic self-awareness permeating all dimensions of life (Fuchs, 2015), i.e., the *ipseity* (Sass & Parnas, 2003). Ipseity represents the most inner nucleus of self-experience within a built-in three-layer model of selfhood[7]. It is the most implicit and pre-reflective form of self-reference: It is readily given to us without necessity of introspection and inference. Any experience we have implies this tacit form of self-awareness, meaning that it underpins every perception, action or thinking. In addition, it is thought to be the medium in which intentional acts can articulate. Finally, ipseity is intrinsically grounded in the lived body, a fact entailing a primitive sense of self-affection. Multisensory integration of constantly-present body-oriented senses (proprioceptive, vestibular, interoceptive sensations) has been proposed to provide the biological substrate for this very basic sense of Self (Postmes et al., 2014). This approach posits that schizophrenia holds a dramatic disintegration of ipseity. Ipseity disruption is two-faceted (Sass, 2014). On the one hand, it shows up as diminished self-affection, e.g., sense of inner void, lack of presence, loss of contact from the body and sense of alienation from the world (Fuchs, 2015). As complementary phenomenon, patients may develop *hyper-reflexivity* and *self-objectification*,

[7] This model includes three levels of selfhood, i.e., the "*minimal self*" (which is, the ipseity), the "*reflective self*" and the "*narrative self*". The narrative self is the psychological, biographical, social and historical knowledge we have accumulated about ourselves. The reflective self is the conscious awareness of being the subject of experience and acts.

meaning they start being engaged in an abnormal form of self-reference in which experiential contents normally felt as immediately "mine" and self-evident, become objects of focal attention, e.g., spontaneous popping-out of inner phenomena, like somatic sensations or fragments of internal thought which engender a strong attentional engagement (Sass, 2014).

Hypohedonia represents one of the many facets of disturbed self-awareness and presence (Parnas et al., 2005). Sass suggested that the abnormal susceptibility of schizophrenic patients to classic RHI might be tied to the collapse of ipseity (Sass, 2014). In regard to the correlation found between anhedonia and sense of ownership within the anticipation-based RHI (Ferri et al., 2014), Gallese and Ferri put forward the hypothesis that this result, along with findings from other studies[8] might represent an empirical outcome of the disruption of the ipseity - the bodily Self - whose primary expression lies in the sense of "*ownership for a body having power for action*" and whose neural substrate would be represented by the ventral premotor cortex[9] (Gallese & Ferri, 2014).

[8] For instance, participants with schizophrenia were found to not show the self-advantage effect in the implicit recognition of own body effectors compared to others' bodily effector and inanimate objects. This effect may demonstrate an impairment at the very basic processing of self-bodily stimuli, maybe highlighting a disturbed sense of bodily Self (Ferri, Frassinetti, Mastrangelo, et al., 2012)

[9] The involvement of the ventral premotor area in the processing of the bodily Self is suggested by authors because of its functional role in the integration of self-related multisensory stimuli and peri-personal space processing, but also because of its specific activation during the mental rotation of participant's own dominant hand. This latter task is in fact an implicit recognition task where the participant is thought to make a covert motor experience of its own body to accomplish instructions; this permits the bodily Self to emerge (Ferri, Frassinetti, Ardizzi, Costantini, & Gallese, 2012).

3 Beyond visuo-tactile RHI

The longstanding literature on sense of agency in schizophrenia (see 1.2) provides evidence for impaired sensorimotor processes for self-recognition. Given that, it could be expected that this deficiency may have implications on self-body awareness and bodily perception. To address this question, healthy participants and patients diagnosed with schizophrenia are tested at a visuo-motor BOI (Rossetti et al., 2019). This kind of illusion may provide additional information about body representation in schizophrenia with respect to previous RHI studies because it represented a viable way to elicit the joint contribution of sense of ownership and sense of body agency to body awareness.

3.1 Experiment 1

3.1.1.1 Rationale of the study

Foregoing studies addressing body awareness in schizophrenia have exclusively capitalized on RHI. Although it is a well-established method to examine body representation, RHI partially overlooks that relevant link between action and perception in the construction of bodily awareness (Tsakiris & Haggard, 2005a). In fact, this visuo-tactile illusion is characterized by overt ownership sensations, but not by explicit sense of agency, which is an important determinant of body awareness. Sense of body agency is elicited much less and possibly only indirectly, as a carryover effect of ownership modulation. It might be also argued that RHI does lacks ecological validity because it does not involves bodily movements (Tsakiris, Schütz-Bosbach, & Gallagher, 2007). More importantly, it may address to a limited extent body awareness in schizophrenia in the light of literature about sense of agency disturbances in schizophrenia (see 1.2). As such, above-mentioned RHI studies (see 2.2) do represent a relevant, but maybe incomplete, account of the issue under investigation. This study sought to fill in this gap.

Furthermore, a very recent meta-analysis of the studies on body ownership in schizophrenia and schizotypy found null statistical evidence in support of the hypothesis of an abnormal body ownership in schizophrenia because of altered multisensory integration. It is there reasoned that results obtained by previous reports may basically reflect a *response bias* that goes beyond the experimental manipulation itself. This means for instance that patients may refer higher ownership sensations because they are prone to anomalous body sensations (e.g., they also provide higher subjective ratings for body ownership control items), a fact that cannot be accounted for by the incapability to detect temporal discrepancies by multisensory integration processes (Shaqiri et al., 2018). By also carrying out the investigation of a full body illusion in patients, Shaqiri et al. (2018) have not found evidence for differential intensities of the illusion in the clinical group. As such, they endorse the reconsideration of the body awareness in schizophrenia.

3.1.1.2 Aims

The main goal of the current study is to investigate the contribution of putative disturbances of self-agency to body awareness in schizophrenia. To the best of our knowledge, whether disrupted sense of agency (either hypo- or hyper-attribution of self-agency) and related sensorimotor processes affect the embodiment illusion in participants with schizophrenia has not been investigated yet.

To address sensorimotor integration underlying embodiment, the Mirror Box (MB) illusion is here *ad hoc* revised to be used as an active variation of the RHI. This paradigm permits the induction of the illusory sense of incorporation of an extra-corporeal hand by visually superimposing the image of an alien hand (like the hand of an experimenter) onto the hand of the participant through a mirror. By capitalizing on the visuo-proprioceptive congruency between the real and the seen hand, different degrees of ownership illusion can be elicited. Participants usually experience that the mirrored hand is part of their body when the mirrored hand mimics their own hand movements. An important aspect for the purpose of the experiment is the possibility to concurrently elicit both agency and ownership sensations for the alien hand, by adopting this visuomotor version of the RHI.

To probe the occurrence of the MB illusion, two measures were collected: the Embodiment questionnaire ratings to assess conscious feelings of incorporation of the external limb (Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008), and the forearm bisection task (D'Angelo, di Pellegrino, Seriani, Gallina, & Frassinetti, 2018; Garbarini et al., 2015; Romano, Uberti, Caggiano, Cocchini, & Maravita, 2019; Sposito, Bolognini, Vallar, & Maravita, 2012; Tosi, Romano, & Maravita, 2018) to measure post-MB changes in the perception of limb extension. In this regard, previous studies brought evidence that body metric representation is malleable. The active training of the limb can modulate body metric representation inducing a shift of the estimation of the forearm midpoint toward the hand (D'Angelo et al., 2018; Garbarini et al., 2015; Romano et al., 2019; Sposito et al., 2012; Tosi et al., 2018). Additionally, a recent study (Tosi et al., 2018) suggests that the update of body metric representation can occur even when one performs motor training while embodying another person's hand by means of the MB. The rationale is that "*E is embodied if and only if some properties of E are processed in the same way as the properties of one's body*" (Frederique de Vignemont, 2010; p. 84). In agreement with this definition, a MB training in post-stroke patients induced an update of affected limb metrics perception as a plausible consequence of the embodiment of the mirrored image of the unaffected hand as if the impaired hand was still able to move (Romano, Bottini, & Maravita, 2013; Tosi et al., 2018).

As regards healthy participants, they were expected to show a perceived elongation of the perceived limb length and stronger feelings of ownership and agency for the alien hand according to the extent of visuo-motor congruency experienced during the MB training. Because of the impairment in agency-related processes, participants with schizophrenia were instead expected to show an altered modulation of explicit as well as implicit indexes of embodiment.

3.1.2 Methods

3.1.2.1 Subjects

Thirty-one patients with a diagnosis of schizophrenia were recruited from the outpatient community service ASST Fatebenefratelli - Sacco (Milan) and from Bolzano Hospital Mental Health department. Diagnosis for schizophrenia was made by treating psychiatrists and confirmed through the Structured Clinical Interview for DSM-IV-TR (First, Spitzer, Gibbon, & Williams, 2002). Current severity of psychopathological symptoms has been evaluated through the Scale for the Assessment of Negative Symptoms and the Scale for the Assessment of Positive Symptoms (Andreasen, 1984, 1989). All patients were receiving stable dose of antipsychotic medications at the time of the assessment. Two patients were excluded because they did not meet criteria for schizophrenia diagnosis. Thirty-six healthy participants were enrolled by word of mouth and by the online recruitment system of Department of Psychology (University of Milano-Bicocca).

The Ethical Committee of the University of Milano-Bicocca and the Ethical Committees of Fatebenefratelli - Sacco Hospital (Milan) and of Bolzano Hospital approved the study. The study was carried out in accordance with the principles of the Declaration of Helsinki (World Medical Organization, 1996). All participants provided written informed consent.

3.1.2.2 Experimental procedure

Participants underwent three experimental conditions, each one consisting of four phases (Figure 1): (1) the pre-training bisection task, (2) the MB training session, (3) the post-training bisection task and (4) the embodiment questionnaire. Before starting the experiment, they were invited to remove bracelets and rings to enhance visual similarity between experimenter's and participant's limb during MB training. To avoid noisy tactile and proprioceptive clues during MB and bisection tasks, participants were often reminded to keep the tested limb still; once post-training bisection task ended, they could move their arm to restore baseline somatic feedback. The study was carried out by two experimenters.

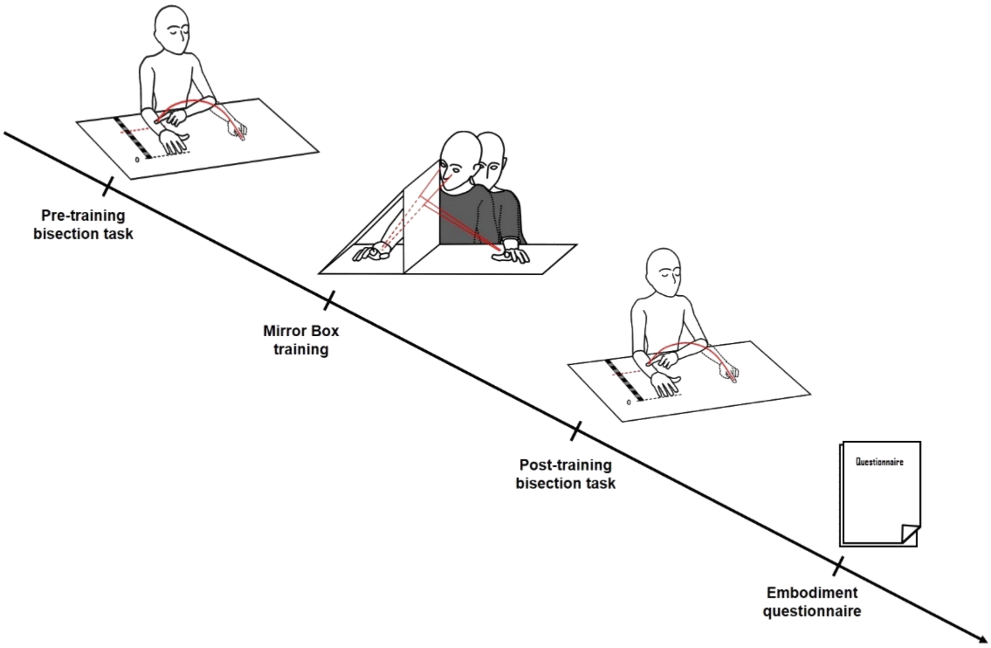


Figure 1. Experimental procedure. *The experimental procedure was repeated three times in order to vary the extent of visuo-proprioceptive congruency experienced during the MB training. The mirror reflection, which provides the image of an extra-personal limb located in the same position of their limb behind the mirror from an egocentric perspective, specifically allowed the dissociation of afferent visual and proprioceptive input. Indeed, the proprioceptive reafference remained constant across conditions as participants always performed the same movement, whereas the visual feedback could be congruent or incongruent with participant's movements. Questionnaire statements aimed at assessing the explicit component of embodiment. Bisection task instead aimed at probing the perceptual aspect of embodiment.*

The first experimenter performed the movements that were reflected in the mirror and administered the questionnaire, while the second experimenter controlled for participants tapping at the proper rate during MB training and measured the endpoint of bisection trials.

MIRROR BOX TRAINING

After the pre-MB bisection task, participants were required to keep their eyes closed, to hold the upper limb (shortly before bisected) still on the table and to put the other one under the table. The MB apparatus (i.e., a triangle MB with a 60 × 50 cm reflective surface) was arranged so that the mirror was parallel to participant's midsagittal plane and his/her limb was inside the MB. The experimenter sat near the participant, placing his limb on the table in order that its reflection looked visually co-located to participant's limb behind the mirror. To reduce visual interference due to the anatomical implausibility of the experimenter's limb, a black cloth covered the participants' trunk and experimenter's shoulder.

During the training participants had to raise and lower the index of the hidden hand for 1 minute, following a metronome beating at 1 Hz. Meanwhile, they had to look at experimenter's hand in the mirror. To reduce cutaneous inputs, they were instructed to avoid touching table surface with index

	SCZ (*n* = 29)	CTR (*n* = 36)
Age, Years	41.34 (14.12)	25.75 (7.86)
Sex, Male/Female	18/11	6/30
Handedness, Right/Left/Ambidextrous	25/3/1	31/5/0
Education, Years	12,41 (2.83)	15.44 (2.32)
SANS		
Affective flattening	3.28 (1.04)	–
Alogia	2.90 (0.90)	–
Avolition - Apathy	3.90 (0.81)	–
Anhedonia - Asociality	3.92 (1.05)	–
Attention	3.44 (1.23)	–
SAPS		
Hallucinations	1.65 (1.16)	–
Delusions	2.06 (1.08)	–
Bizarre behavior	2.90 (1.54)	–
Formal thought disorders	2.30 (1.10)	–
Antipsychotic medication		
First Generation	2	–
Second Generation	26	–
Both	1	–

Table 3. Sample demographics*. Values are presented as n or mean (SD). CTR, healthy controls; SCZ, schizophrenic patients; SANS, Scale for the Assessment of Negative Symptoms; SAPS, Scale for the Assessment of Positive Symptoms.*

finger. Participants were exposed to three different types of (alien) visual feedback: (1) *In-Phase*: the experimenter tapped at the same frequency and in the same direction, i.e., lowering the index at every beat; (2) *In-Antiphase*: the experimenter tapped at the same frequency, but 180° out-of-phase, i.e., raising the index at every beat; and, (3) *Random*: the experimenter accomplished completely different finger movements, i.e., following casual trajectories and irregular frequency. The order of conditions and hand laterality were counterbalanced across participants.

BISECTION TASK

In bisection task participants were asked to arrange forearms in parallel position and to point at the middle of the tested limb with the contralateral hand. They were instructed to consider the limb length ranging from the elbow to the tip of the middle finger. Pointing movements had to be as straight as possible, without online corrections once started.

Participants performed 10 pointing movements during each bisection task; as the task both preceded and followed each MB training, a total of 60 repetitions per subject were collected, i.e., 10 trials × 2 bisection tasks (Pre-MB, Post-MB) × 3 conditions (In-Phase, In-Antiphase, Random). We measured both the subjective midpoint (i.e., the distance between the middle fingertip and the point indicated by the subject) at each trial and the total length (i.e., the distance between the middle fingertip and the olecranon). To normalize participants' bisection estimates, the ratio between the two measures was calculated [*R* = *subjective midpoint/total length*] (Sposito et al., 2012).

SELF-REPORT

At the end of each block participants retrospectively rated their subjective experience during the MB training via a 27-item questionnaire. Statements were translated in Italian and adapted from the RHI embodiment questionnaire (Longo et al., 2008) (Appendix 1). Particular attention was paid to the assessment of the Embodiment component of illusion and its subcomponents. *Ownership* items variously describe the feeling that the mirrored hand is likely to belong to one's own body; *Location* items refer to a sense of spatial congruency between one's own hand and the mirrored hand; *Agency* statements concern the sense of being the agent of the movements performed by the mirrored hand.
Participant had to verbally refer to what extent they agree/disagree with each statement by referring to a 7-point Likert scale presented on a sheet of paper (+3: strong agreement; 0: neither agreement nor disagreement; -3: strong disagreement). Items were read to participants and explained if needed.
To rule out participants' response style effect, a within-subject standardization was adopted [*Ipsatisation:* $y' = (x\text{-}mean_{individual})/SD_{individual}$] (Fischer & L. Milfont, 2010). Components scores were calculated from ipsatisation rates.

3.1.2.3 Data analysis

Bisection *R* values were analyzed via linear mixed-effects model (*lmer* function; lme4 package (Bates & Sarkar, 2006). Maximum Likelihood criterion was used to estimate fixed and random parameters, whereas models' goodness of fit was compared by Likelihood Ratio test. Initially, a fixed intercept and by-subject random intercepts model was built to control for repeated-measure structure of data. To further specify random structure, *Trial* was entered as grouping factor and checked for model goodness-of-fit. Then, *Group*, *Congruency* and *Time* of bisection task and their interactions were incrementally added as fixed effects and retained when they improved model goodness-of-fit. Lastly, a Type III mixed-design ANOVA was performed on the final model. Questionnaire scores relating to each component were analyzed through separate 2 (between-subject factor *Group*) ×3 (within-subject factor *Congruency*) ANOVAs for unbalanced data (*aov_ez* function; *afex package* (Singmann, Bolker, Westfall, & Aust, 2017). Finally, an exploratory correlation analysis was computed between questionnaire components (mean cores calculated on raw data) and psychopathological scales.
All data analyses were carried out with R 1.1.463 (R Core Team, 2019).

3.1.3 Results

3.1.3.1 Bisection judgements

Bisection data were modeled as depending on all experimental predictors (fixed covariates: *Group*, *Congruency* and *Time*) after adjusting for random effects *Trial* and *Subject* (see Supplementary Material). Analysis of variance run on the final model revealed significant differences for the two-way interaction *Group* × *Congruency* [$F_{2, 3826.1} = 4.419$; $p = .012$] and the three-way interaction *Group* ×

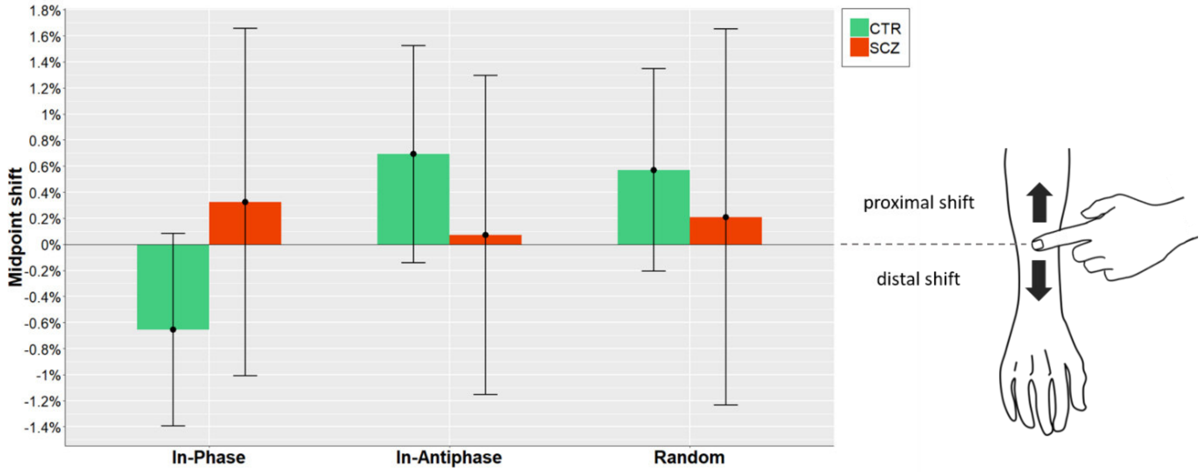


Figure 2. Midpoint shift following MB training. *Bars represent mean differences (± 95% CI) between bisection performance before and after MB training. The shift is reported as percentage of the total forearm and hand length. Negative values reveal a shift towards the hand (distal shift), while positive values indicate a shift towards the elbow (proximal shift). Midpoint displacement for different experimental conditions and groups are depicted. CI were calculated with summarySEwithin function.*

Congruency × *Time* [$F_{2,3826.1} = 4.562$; $p = .01$]. Conversely, main effects *Group* [$F_{1,65} = 0.595$; $p = .443$], *Congruency* [$F_{2,3826.1} = 2.392$; $p = .092$] and *Time* [$F_{2,3826.1} = 3.006$; $p = .083$] and two-way interactions *Group* × *Time* [$F_{2,3826.1} = 0.001$; $p = .980$] and *Congruency* × *Time* [$F_{2,3826.1} = 2.496$; $p = .083$] were not significant.

To examine the three-way interaction, the mean post-MB midpoint displacement and 95% Confidence Interval (CI) were calculated. Controls showed a distal shift equal to .66% [CI: -1.39; .08] after the *In-Phase* MB training, but a proximal shift after both control conditions (*In-Antiphase*: .69% [CI: -.14; 1.52]; *Random*: .57% [CI: -.21; 1.35]). Patients displayed a less defined pattern, with a moderate proximal shift in all conditions (*In-Phase*: .33% [CI: -1.01; 1.66]; *In-Antiphase*: .07% [CI: -1.15; 1.30]; *Random*: .21% [CI: -1.23; 1.65]) (Figure 2).

3.1.3.2 Questionnaire responses

Significant effects were explored through graph inspection (Figure 3). Ipsatisation makes between-group comparisons unreliable because adjusted scores represent deviations from the within-subject mean, which is 0 (Fischer & L. Milfont, 2010); however, within-subject variance across conditions and interaction effects are not affected this procedure and reliably interpretable. Therefore, significant main effect *Group* will be mentioned, but not commented on. The effect size statistics for between-within designs (η_G^2) will be provided (0.02: small, 0.13: medium, 0.26: large) (Bakeman, 2005).

Embodiment: both main effects *Group* [$F_{1,63} = 9.988$; $p = .002$; $\eta_G^2 = .06$] and *Congruency* [$F_{2,126} = 11.196$; $p = <.001$; $\eta_G^2 = .09$] were significant, but not the interaction effect *Group* × *Congruency* [$F_{2,126}$

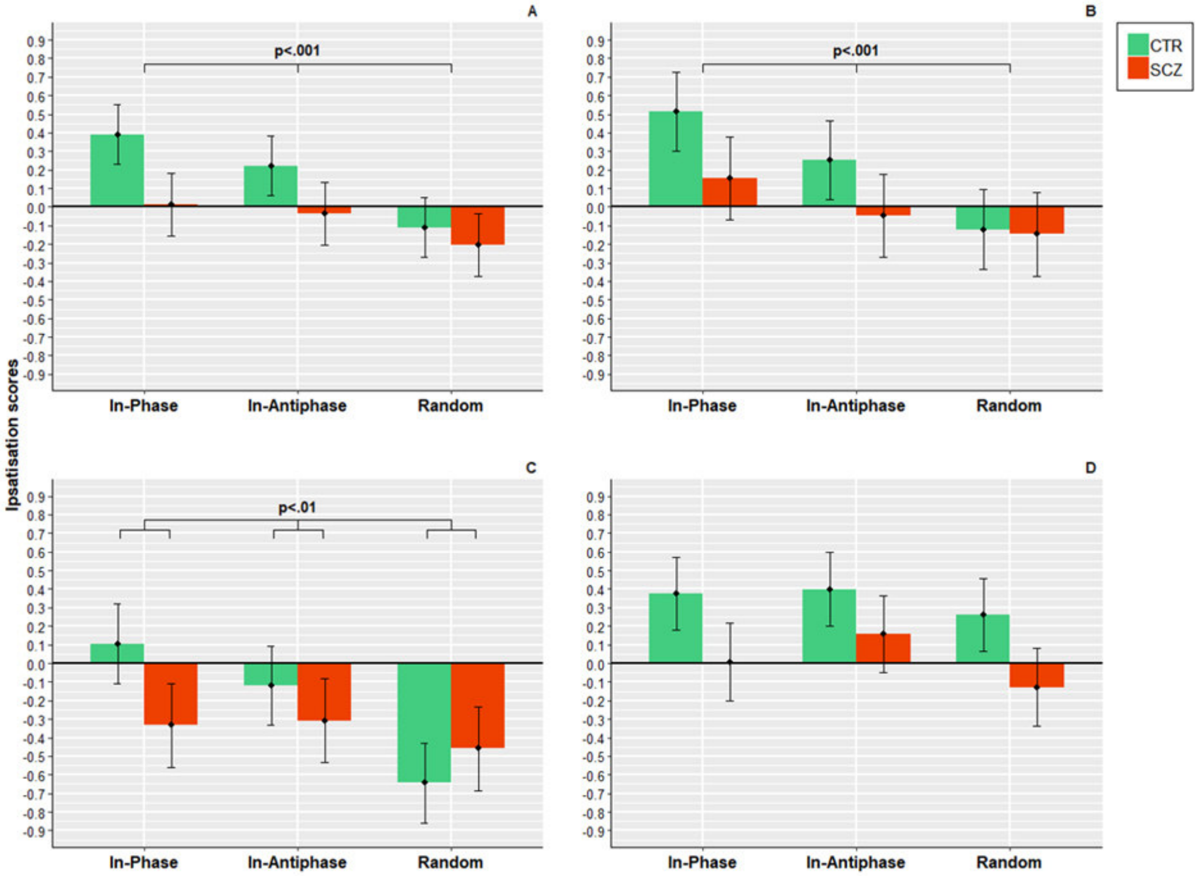


__Figure 3. Embodiment questionnaire ratings__. Bar graph depicts estimated marginal means of ratings of the Embodiment component (panel A) and its subcomponents Ownership (panel B), Agency (panel C) and Location (panel D) for different experimental conditions and groups.

= 1.691; p = .189; η_G^2 = .01]. Ownership: both the main effects *Group* [$F_{1,63}$ = 3.891; p = .053; η_G^2 = .03] and *Congruency* [$F_{2,126}$ = 12.760; p <.001; η_G^2 = .08] were significant, but not the interaction effect *Group* × *Congruency* [$F_{2,126}$ = 1.839; p = .163; η_G^2 = .01]. Agency: the main effect *Group* [$F_{1,63}$ = 1.661; p = .202; η_G^2 = .01] was not significant, but the main effect *Congruency* [$F_{2,126}$ = 11.899; p <.001; η_G^2 = .08] and the interaction effect *Group* × *Congruency* [$F_{2,126}$ = 5.561; p = .005; η_G^2 = .04] were significant. Location: the main effect *Group* [$F_{1,63}$ = 11.375; p = .001; η_G^2 = .08] was significant, but the main effect *Congruency* [$F_{2,126}$ = 2.699; p <.071; η_G^2 = .02] and the interaction effect *Group* × *Congruency* [$F_{2,126}$ = 0.388; p = .679; η_G^2 = .003] were not.

These results indicate that the general embodiment sensation and the feeling of ownership for the alien hand were driven by the degree of visuo-motor congruency in both groups: the higher the visuo-motor congruency, the higher the rates provided by subjects. Instead, the sense of agency, which follows the extent of visuo-motor congruency in controls, stands on average at similar values across conditions in patients.

3.1.3.3 Correlation analysis

Correlation analysis suggests that hallucination severity moderately correlated with Ownership (r_S = .41, p_{uncorr}=.026), Location (r_S = .41, p_{uncorr}=.026), Agency (r_S = .43, p_{uncorr}=.021) and Movement (r_S = .38, p_{uncorr}=.045) scores in *Random* condition. Location items related to In-Phase condition mildly correlated with alogia severity (r_S = .41, p_{uncorr}=.029). For overview of these correlations, see Table 5.

3.1.4 Discussion

In this study, we aimed to test the impact of sense of agency impairment on embodiment in people suffering from schizophrenia. The MB illusion specifically allowed to concurrently modulate ownership and agency subcomponents of the bodily-awareness in participants.

As expected, cross-modal coherence between reafferent signals (i.e., the visual feedback from the alien hand and the proprioceptive feedback from the participant's hand) can evoke feelings of embodiment for the hand in the mirror in healthy people (Holmes, Snijders, & Spence, 2006; McCabe, Haigh, Halligan, & Blake, 2005; Medina, Khurana, & Coslett, 2015; Romano, Caffa, Hernandez-Arieta, Brugger, & Maravita, 2015). This result also agrees with the proposal that the coherence between afferent and efferent information increases the likelihood that an extra-personal limb is tagged as "mine" (Apps & Tsakiris, 2014), albeit obvious morphological differences. In the current study, when the alien hand kinematically mimicked participant's hand movements, the visual feedback in the mirror could effectively approximate predictions. The generation of internal predictions is thought to enable the sensorimotor system to precisely anticipate temporal and postural parameters of the movement that is just about to be accomplished, crucially improving Self recognition (Tsakiris, Haggard, Franck, Mainy, & Sirigu, 2005). We hypothesize that an "inclusion" of the image of the alien limb within one's own body representation may occur during the MB training (Romano et al., 2013; Tosi et al., 2018). Specifically, the prolonged view of an alien hand moving in accordance with motor predictions would lead comparator mechanisms to embody it as a self-generated sensory feedback. The visual feedback provided by the alien hand might then be used by the motor system to feed up the dynamic short-term sensorimotor representations serving action program and guidance (Frederique de Vignemont, 2010).

Bisection data show that the strength of visuo-proprioceptive congruency also impacts on perceived body metrics. Indeed, the post-MB estimation of limb length increases/decreases along the forearm proximo-distal axis across conditions. The distal midpoint shift after the In-Phase condition replicates Tosi et al.'s study (2018), wherein hemiplegic patients showed an extension of the perceived length of the paretic limb induced by the motor training with MB.

The bidirectional relocation of the subjective midpoint observed here is suggestive of a relative "elongation" of the limb representation when embodiment of the alien hand occurs, but of a "shortening" when embodiment is prevented. These effects are consistent with the hypothesized plastic

	Affective Flattening	Alogia	Apathy	Anhedonia	Attention	Hallucinations	Delusions	Bizarre Behaviour	Formal Thought Disorder
Ownership									
Phase	-0.06(0.766)	0.28(0.139)	0.22(0.254)	0.16(0.415)	0.24(0.212)	0.1(0.601)	0.11(0.584)	0.1(0.595)	-0.03(0.884)
Antiphase	-0.28(0.141)	0.08(0.683)	-0.06(0.763)	-0.13(0.518)	-0.15(0.425)	0.05(0.79)	-0.15(0.425)	-0.22(0.257)	-0.31(0.097)
Random	-0.15(0.441)	0.02(0.928)	0.15(0.443)	0.26(0.172)	0.03(0.875)	0.41(0.026)	0.15(0.444)	0.12(0.549)	0.02(0.921)
Location									
Phase	0.04(0.84)	0.41(0.029)	0.18(0.344)	0.06(0.752)	0.16(0.401)	0.16(0.413)	-0.04(0.852)	0.11(0.577)	-0.04(0.833)
Antiphase	0(0.981)	0.3(0.119)	0.08(0.688)	0(0.983)	0(0.989)	0.11(0.584)	-0.18(0.337)	0.02(0.909)	-0.14(0.454)
Random	-0.07(0.731)	0.06(0.753)	0.24(0.219)	0.26(0.176)	0.08(0.669)	0.41(0.026)	0.27(0.157)	0.24(0.218)	0.04(0.819)
Agency									
Phase	-0.12(0.521)	0.21(0.269)	0.13(0.488)	0.08(0.677)	0.08(0.695)	0.21(0.263)	0.04(0.837)	0.15(0.426)	-0.01(0.978)
Antiphase	-0.05(0.789)	0.2(0.302)	0.17(0.365)	0.08(0.676)	0.12(0.52)	0.11(0.579)	0.11(0.555)	0.09(0.634)	0.05(0.808)
Random	0.01(0.957)	0(0.993)	0.28(0.137)	0.23(0.239)	0.01(0.977)	0.43(0.021)	0.17(0.39)	0.3(0.118)	0.18(0.345)
Loss of own hand									
Phase	-0.04(0.843)	0.14(0.481)	0.14(0.466)	0.05(0.788)	0(0.984)	0.28(0.144)	-0.17(0.386)	-0.07(0.73)	-0.06(0.767)
Antiphase	-0.01(0.973)	0.29(0.128)	0.08(0.661)	0.08(0.69)	0.09(0.63)	0.16(0.407)	0.11(0.557)	0(0.998)	0.02(0.905)
Random	-0.08(0.684)	-0.04(0.851)	0.05(0.797)	0.05(0.793)	-0.12(0.546)	0.26(0.18)	0.04(0.85)	-0.01(0.974)	-0.04(0.852)
Movement									
Phase	0(0.993)	0.32(0.094	0.11(0.582)	0.1(0.622)	0.08(0.681)	0.29(0.133)	0.05(0.788)	0.06(0.743)	-0.08(0.68)
Antiphase	-0.26(0.182)	0.05(0.787)	-0.02(0.918)	-0.02(0.931)	-0.16(0.41)	0.31(0.103)	0.09(0.625)	-0.08(0.676)	-0.19(0.319)
Random	-0.04(0.848)	0.14(0.454)	0.07(0.715)	0.16(0.41)	0.07(0.705)	0.38(0.045)	0.09(0.651)	0.18(0.354)	-0.03(0.868)
Affect									
Phase	0.19(0.316)	0.05(0.815)	0.2(0.291)	0.07(0.714)	0.31(0.102)	0.07(0.725)	0.08(0.694)	-0.02(0.916)	0.21(0.268)
Antiphase	0.18(0.355)	0.1(0.612)	0.2(0.309)	0.16(0.393)	0.28(0.137)	-0.13(0.491)	0.24(0.211)	-0.06(0.776)	0.21(0.267)
Random	0.2(0.291)	-0.04(0.843)	0.05(0.813)	0.08(0.689)	0.26(0.165)	0.04(0.855)	-0.02(0.909)	-0.02(0.932)	0.14(0.459)

Table 4. Correlation between Embodiment questionnaire components and psychopathological scales. *Spearman's correlation coefficient (uncorrected p-value). Strength of association between questionnaire components of embodiment and the severity of positive and negative symptoms. p-value were uncorrected for multiple testing and should be interpreted cautiously.*

modifications of bodily representation serving motor control, i.e., the body schema (Berlucchi & Aglioti, 2010). We propose that post-MB bisection shifts may reflect top-down regulation of proprioception when body schema update is induced by the MB training. Otherwise stated, body schema may be subject to increased/reduced weighting of the hand segment representation as a result of the extent of visuomotor congruency experienced during the MB training. Such an update may in turn induce an increased/reduced proprioceptive representation of the hand, as suggested by the distal and proximal shifts. This hypothesis agrees with the previously suggested dampening of proprioception following sensorimotor incongruency (Medina et al., 2015). Conversely, a mere effect of multiple muscles and joints activation and/or of the sustained visuo-spatial attention on the hand can be ruled out because, if this were the case, the midpoint shift would have been constantly distal across conditions.

Unlike healthy controls, patients exhibited similar levels of agency across conditions. Consistently, bisection performance does not show a clear trend of proximo-distal modulation (see CI, Figure 2). Overall, these results suggest that these aspects of the illusion are not driven by visuo-proprioceptive congruency in schizophrenia. Two, not mutually exclusive, impairments might explain these findings.

On the one hand, they might depend on the putative defective computation of motor predictions (van der Weiden, Prikken, & van Haren, 2015). Impaired predictions might have prevented the correct detection of kinematic similarities/dissimilarities in the mirrored hand, abolishing the modulation of the agency ratings across conditions. Furthermore, the high variance of bisection performance may support the hypothesis that internal motor prediction in schizophrenia is highly unreliable, as suggested by Synofzik et al. (2010). In this study, when asked to indicate the visual endpoint of pointing movements previously performed in the absence of visual feedback, patients demonstrated greater inter-trial variability than controls. Given that endpoint estimation could be based on internal cues only, these results have been interpreted as a possible index of highly variable internal predictions (Synofzik et al., 2010). Accordingly, it is likely that the comparison between predicted and actual feedback, which would contribute to the inclusion of the alien hand within one's own body schema, is also affected by high variability. As a result, the modulation of body metrics cannot clearly emerge. It is worth noticing, however, that other reasons for this high variability cannot be completely ruled out. For instance, the previously found link between passivity profile and body representation distortions (Graham-Schmidt, Martin-Iverson, Holmes, & Waters, 2016; Graham et al., 2014). We carried out a posteriori analysis, dividing schizophrenia group according to passivity symptom severity. Nonetheless, an unclear trend of bisection performance still resulted, conceivably because of small subgroup size (Appendix 1). Moreover, deficits of sustained attention in schizophrenia (Hoonakker, Doignon-Camus, & Bonnefond, 2017) may play a role because fluctuations in the maintenance of the attentional focus on the mirrored hand may have altered embodiment processes.

A second potential explanation for the anomalous modulation of embodiment indexes is the width of the temporal binding window (TBW), i.e., the time interval within which different sensory stimuli are very likely to be bound in the same percept. Prior work has shown wider visuo-proprioceptive TBW in schizophrenia (Franck et al., 2001) with respect to healthy people (Franck et al., 2001; Ismail & Shimada, 2016; Shimada, Qi, & Hiraki, 2009). Therefore, lack of agency and bisection performance modulation might relate to lower multisensory temporal acuity. Interestingly, Ferri et al. (2017) showed that audio-tactile TBW, which is positively associated to the level of cognitive-perceptual schizotypy (an index of psychoses proneness), can be predicted by the temporal structure of spontaneous activity in auditory cortex. A causal link between temporal properties of resting-state neural fluctuations and multisensory TBW has been postulated in the "spatiotemporal" model of schizophrenia (Northoff & Duncan, 2016), which posits that the breakdown of intrinsic brain's activity dynamics (both at spatial and temporal level) constitutes the neurobiological substrate of different psychopathological symptoms. In the case of ego-disturbances (like agency disruption), the unbalance between the Default Mode Network, which is highly implicated in self-related processing, and Central Executive Network, conversely devoted to the processing of exogenous stimuli, would entail the pathological mixing of internally- and externally- oriented thoughts (Northoff & Duncan, 2016; Robinson, Wagner, & Northoff, 2016). Accordingly, reasons for the abnormal trend of bisection data and sense of agency might lie in the impairment of bottom-up sensory mechanisms and in the afore-mentioned impossibility to discretely distinguish between internal *vs.* external perceptual contents. As regards correlation analysis, we avoided strong claims based on it given that it was mainly for exploratory purposes.

To conclude, this study yields two main findings. First, perceived body metrics, in healthy individuals, bidirectionally update according to the strength of embodiment illusion, an effect that is compatible with an online reconfiguration of body schema. Second, patients did not demonstrate significant body metrics and sense of agency modulation, indicating that not only compromised visuo-tactile integration (Ferri et al., 2014; Graham et al., 2014; Peled et al., 2003, 2000; Thakkar et al., 2011), but also impaired visuo-motor integration, may affect body representation building up in schizophrenia.

3.2 Experiment 1.1

3.2.1.1 Rationale of the study

Some foregoing studies brought evidence that specific motor training accomplished through manual movements can induce a modification in the subjective perception of body metric (e.g., forearm length). Such tasks include for instance tool-use (Garbarini et al., 2015; Romano et al., 2019; Sposito et al., 2012; Tosi et al., 2018). Starting from the idea that "*E is embodied if and only if some properties of E are processed in the same way as the properties of one's body*" (Frederique de Vignemont, 2010; p. 84), a comparable recalibration of forearm metric, at representational level, should occur when one performs finger movements (i.e., movements involving distal segments of the arm) while embodying an alien hand. In other terms, the distal midpoint shift could represent a perceptual correlate of the embodiment of an alien hand performing manual movements.

As mentioned in the previous study, this hypothesis has been recently supported by Tosi et al. (2018) who have found that post-stroke patients show a distal recalibration of the perceived metric of the affect forearm after a short MB training. Importantly, the effect does not show up when patients undergo an analogous training without MB. This difference suggests that MB is a crucial factor in engendering the distal midpoint shift in patients. It is likely that MB acts by restoring the visual feedback from the impaired hand[10]. Under this condition, the re-established matching between intact motor intentions and effective visual feedback from the hand may be responsible for the embodiment of the contralateral unaffected hand and, accordingly, for the update of the metric component as if the impaired arm was still properly moving. Therefore, the distal shift in patients may have been mediated by the embodiment, which might have been allowed by the integration of the unimpaired mirrored hand within the shrunk representation of the impaired contra-lesional hand.

The fact that the distal midpoint shift may be a perceptual correlate of embodiment is also supported by Experiment 1. In fact, results from the control group show that the incorporation of an alien hand, as demonstrated by higher subjective sensations of ownership and agency in the In-Phase condition, is accompanied by the distal midpoint shift. It is likely that the sensorimotor system is led by MB to use the reflected image of the alien hand as the visual feedback from own hand and, when the visual feedback matches the intended movement, the alien hand is accepted as plausible feedback and integrated into one's own body representation. The modulation of the forearm length representation may represent a perceptual index of such an integration process. The distal midpoint shift after MB training may accordingly indicate that the metric component of the arm representation is processed as

[10] In post-stroke patients a preserved intention-to-move is followed by movement that does not properly match the intended one because of degenerated motor abilities. Therefore, seeing the ipsilesional unaffected hand through the mirror superimposed on the location of the affected one does properly re-establish the visual feedback of the attended movement.

usual. This hypothesis is further supported by the proximal shift observed in the incongruent conditions. In those conditions, the metric component of body representation cannot be processed as usual because the incongruent visual information unbalances and/or prevent embodiment (Rossetti et al., 2019).

While it is likely that the modulation of the metric component of the internal representation of the forearm may represent a perceptual correlate of embodiment, why it occurs during the performance of a manual movement is not clear yet. Different, non-mutually exclusive, mechanisms driving the midpoint shift have been hypothesized.

The distal midpoint shift has been consistently found to occur after tool-use (Garbarini et al., 2015; Romano et al., 2019; Sposito et al., 2012). Sposito et al. (2012) for instance suggested that the forearm midpoint distal shift after tool-use is indicative of an elongation of the forearm representation when acting with a tool (as though the tool was embodied into body schema)[11]. Other hypothesized mechanisms are the extension of the reaching space by means of the tool (Garbarini et al., 2015), the selection of specific motor patterns and the functional use of the tool (Romano et al., 2019) and the sense of agency over expected consequences of action in space (D'Angelo et al., 2018).
However, the distal shift has been also found to follow manual movements without tool, even though to a lesser extent than tool-use training (Romano et al., 2019; Rossetti et al., 2019; Tosi et al., 2018). For instance, Romano and co-workers (2019) found that when participants are trained to do the same action with the same scope with or without a tool in the hand, there is a shift in the body bisection task following the training in any case. This latter finding is interesting because it suggests that the body metrics rescaling is strengthened by tool-use, but it is not straightforwardly triggered by it.

3.2.1.2 Aims

As the previous study highlights, the forearm midpoint and the sense of agency do not modulate across condition in the schizophrenic group. On a general ground, this result might indicate that sense of agency and the distal relocation of the forearm midpoint are functionally linked. That is, being in control of the hand, which is usually accompanied by the subjective sensation of agency, might trigger the rescaling of the internal body representation of the upper limb. Such a phenomenon might facilitate the motor control over the limb. Consequently, when the individual is required to estimate the forearm midpoint only using proprioceptive information (because the bisection task is performed with eyes closed) immediately after the execution of the movement, it could be that the internal representation rescaling is detectable through his/her bisection performance.

The aim of the current study was therefore to investigate whether the occurrence of sense of agency, intended as the feeling of intending the movement and the sense of control over consequences,

[11] This study demonstrated that tool-use does not only have a modulatory effect on peri-personal space, as extensively investigated by other studies - for a recent review: Maravita & Romano (2018) - but it can also induce a dynamic modulation of body representation and specifically of its metric component.

represents a crucial trigger for the distal shift of the forearm midpoint. To address this question, the experimental design used in this study made use of the well-established dichotomy between active and passive movements. Active and purposeful movements give rise to both sense of ownership and sense of agency over the moving hand, whereas involuntary movements, like those due to the passive displacement of a body part, can only elicit sense of ownership over it (Gallagher, 2000). Based on this, sense of agency and sense of ownership could be methodologically dissociated (Braun, Thorne, Hildebrandt, & Debener, 2014; Dummer, Picot-Annand, Neal, & Moore, 2009; Kalckert & Ehrsson, 2012, 2014a; Kalckert & H. Ehrsson, 2017; Tsakiris, Prabhu, & Haggard, 2006). In fact, this distinction also allows to separate the afferent and efferent signals arising during the generation of a movement. Active and passive movements engage the same afferent information, i.e., proprioceptive and visual signals. However, only active movements are initiated and controlled by the individual and for that reason they notably imply the recruitment of efferent information, i.e., the motor command and motor predictions based on the efferent copy (Tsakiris et al., 2007).

3.2.2 Methods

3.2.2.1 Subjects

Forty-eight healthy volunteers (17 males and 31 females; mean age ± s.d.: 24.29 ± 5.85 years; mean educational level: 16.81 years) accepted to participate in the experiment. Most of them were students enrolled by word of mouth and by the online recruitment system of Department of Psychology (University of Milano-Bicocca). The Ethical Committee of the University of Milano-Bicocca approved the study. The study was carried out in accordance with the principles of the Declaration of Helsinki (World Medical Organization, 1996). All participants provided their written informed consent. Students received course credits for their participation.

3.2.2.2 Experimental procedure

The experimental procedure was basically the same of the previous experiment (see 3.1.2.2) except for the experimental design adopted here. The experiment was designed to control for two explanatory variables, i.e., the *Mode of Movement* (Active Movement *vs.* Passive Movement) and the degree of *Congruency* between visual and proprioceptive feedbacks (In-Phase, In-Antiphase). As in the prior experiment, each condition consists in (1) Pre-training bisection task, (2) MB training, (3) Post-training bisection task and (4) Questionnaire.

MIRROR BOX TRAINING

As in experiment described in 3.1.2.2 the participant was asked to perform index finger movement with the hand behind the mirror while looking at the experiment's hand in the mirror. However, an *ad hoc* apparatus was used to fulfil the experimental requirements, i.e., the performance of active or passive finger movements.

The apparatus consisted of two levers, one behind the mirror and the other one in front of it. The two levers were connected through mechanical transmission in a manner that by pressing one lever, the other one also moved (Figure 4). To reduce cutaneous input due to the rubbing of the fingertip against the surface of the lever, the pad was stuck to the lever by a little piece of double-sided adhesive tape. Each MB training lasted 1 minute.

Participants were exposed to two types of (alien) visual feedback: (1) *In-Phase*: the finger of the experimenter moved on the lever at the same frequency and in the same direction; (2) *In-Antiphase*: the finger of the experimenter moved on the lever at the same frequency, but 180° out-of-phase.

Furthermore, participants were to perform two types of finger movements: (1) *Active movement*: the participant was required to push and release a lever with their index finger with the hand behind the mirror while observing the experimenter hand moving analogously on the other lever. Subjects had to push the lever approximately once a second, finding their own internal rhythm; (2) *Passive movement*: the participant was asked to let the index finger of her/his hand behind the mirror be lower and raised by the lever while he/she was observing the experimenter hand moving similarly on the other lever. Participants were exposed to 1 minute of visuomotor training per condition. The order of conditions and hand laterality were completely randomized across participants. Overall, participants underwent four experimental conditions in total.

BISECTION TASK

For a detailed description, see 3.1.2.2.

SELF-REPORT

For a detailed description, see 3.1.2.2.

3.2.2.3 Data analysis

Bisection *R* values were analyzed via linear mixed-effects model - *lmer* function; lme4 package (Bates & Sarkar, 2006). Model selection has been carried out through automatic backward stepwise elimination of the effects introduced in the full model. According to this procedure, random parameters are tested first, then fixed effects are evaluated starting from higher-order interactions. Effects are retained when improve model goodness-of-fit - *step* function; lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2017). Lastly, a Type III mixed-design ANOVA was performed on the final model.

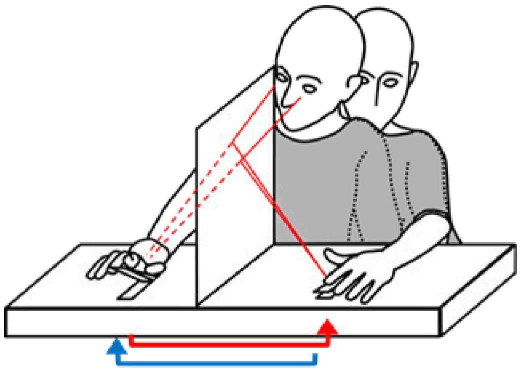


*Figure 4. **Experimental set-up**. A double-lever mechanical device was used. The levers were integrated into a wooden board under which a mechanical system controlled the motion of the levers. The mechanical connection between levers was such that any time the participant pressed the lever behind the mirror, the experimenter index passively moved on the lever in front of the mirror (red arrow). Conversely, during the conditions of passive movement, the experimenter activated the mechanical system by the lever in front of the mirror (blue arrow).*

Questionnaire scores relating to each component were assessed for normal distribution of residuals. Since at least one of subgroups of data failed to meet normality criteria[12] within each component dataset, a non-parametric test for factorial designs has been here used – the *Aligned Rank Transformation test*; ARTool package. ART test is appropriate for multi-factors within-subject designs (Kay & Wobbrock, 2019; Wobbrock, Findlater, Gergle, & Higgins, 2011). All data analyses were carried out with R 1.1.463 (R Core Team, 2019).

3.2.3 Results

3.2.3.1 Bisection judgements

The most parsimonious model evaluated by the stepwise backward selection included both random effects, the three main effects together with the second-order interaction effect *Mode of Movement* × *Time* (Table 6). Analysis of variance run on the final model revealed a significant effect of the two-way interaction *Mode of Movement* × *Time* [$F_{1,3783} = 5.341$; $p = .021$] and of the main factor *Congruency* [$F_{1,3783} = 11.116$; $p < .001$]. Main effects *Mode of Movement* [$F_{1,3783} = 0.853$; $p = .356$] and *Time* [$F_{1,3783} = 0.169$; $p = .681$] were not significant. To examine the two-way interaction, the mean post-MB midpoint displacement and 95% Confidence Interval (CI) were calculated. As depicted in Figure 5, participants showed a proximal shift amounting to .22% [CI: -.3; .74] after conditions they were required to actively press the lever, but a distal shift equal to -.31% [CI: -.84; .21] following conditions in which they were to let their index to be raised and lowered by the lever. Given the current results, the hypothesized interaction between the *Mode of Movement* and the predicted *Congruency* between feedback is not an explanatory effect of bisection performance by participants.

[12] To check for normality of distribution, Q-Q plots, skewness and kurtosis were evaluated. Normality has been assumed for values of skewness and kurtosis between -1 and +1 (Doane & Seward, 2011).

Fixed Structure	B	df	t-value	*p*	lower CI	upper CI
Intercept	0.681	57.17	78.460	<.001	0.664	0.699
MovementPassive	0.001	3783	0.981	0.327	-0.002	0.005
CongruencyIn-Antiphase	-0.004	3783	-3.334	<.001	-0.006	-0.002
TimePost	0.002	3783	1.343	0.179	-0.001	0.005
MovementPassive:TimePost	0.005	3783	-2.311	0.021	-0.009	-0.001
Random Structure						
σ^2_{ID}	0.003					
σ^2_{Trial}	0.000					
σ^2_{Res}	0.001					
N_{ID}	48					
N_{Trial}	10					
ICC_{ID}						
ICC_{Trial}						

Table 5. Fitted linear mixed model and summary statistics. *The upper part lists the fixed parameters estimates (B) and their associated degree of freedom (df), t-value, 95% CI and p-value. The lower part shows random intercepts' variance (σ^2) and intraclass correlation (ICC).*

3.2.3.2 Questionnaire responses

The non-parametric ART test on questionnaire data revealed the following results.
Embodiment: both main effects *Congruency* [$F_{1,141}$ = 142.829; p = <.001; η_p^2 = .5] and *Mode of Movement* [$F_{1,141}$ = 8.824; p = .003; η_p^2 = .05] were significant, but not the interaction effect *Congruency* × *Mode of Movement* [$F_{1,141}$ = 0.177; p = .675; η_p^2 = .001]. Ownership: the main effects *Congruency* [$F_{1,141}$ = 126.102; p = <.001; η_p^2 = .47], whereas the main effect *Mode of Movement* [$F_{1,141}$ = 2.797; p = .097; η_p^2 = .02] and the interaction effect *Congruency* × *Mode of Movement* [$F_{1,141}$ = 0.013; p = .91; η_p^2 = .000] were not. Agency: both main effects *Congruency* [$F_{1,141}$ = 59.979; p = <.001; η_p^2 = .29] and *Mode of Movement* [$F_{1,141}$ = 32.827; p = <.001; η_p^2 = .19] were significant, but not the interaction effect *Congruency* × *Mode of Movement* [$F_{1,141}$ = 0.135; p = .714; η_p^2 = .001]. Location: the main effects *Congruency* [$F_{1,141}$ = 63.628; p = <.001; η_p^2 = .31], whereas the main effect *Mode of Movement* [$F_{1,141}$ = 0.482; p = .489; η_p^2 = .003] and the interaction effect *Congruency* × *Mode of Movement* [$F_{1,141}$ = 1.206; p = .274; η_p^2 = .008] were not.

3.2.4 Discussion

The present study aimed at verifying the hypothesized relationship between sense of agency and bisection performance suggested by Experiment 1. Even though questionnaire data basically replicate prior findings about agency and ownership during active and passive movements, results from bisection performance data do not support the main issue under investigation.

Self-report modulation shows that illusorily sense of ownership for the mirrored hand is stronger during *In-Phase* compared to *In-Antiphase* conditions (Figure 6, panel B), however it does not significantly vary with respect to the type of movement. These results converge with previous studies

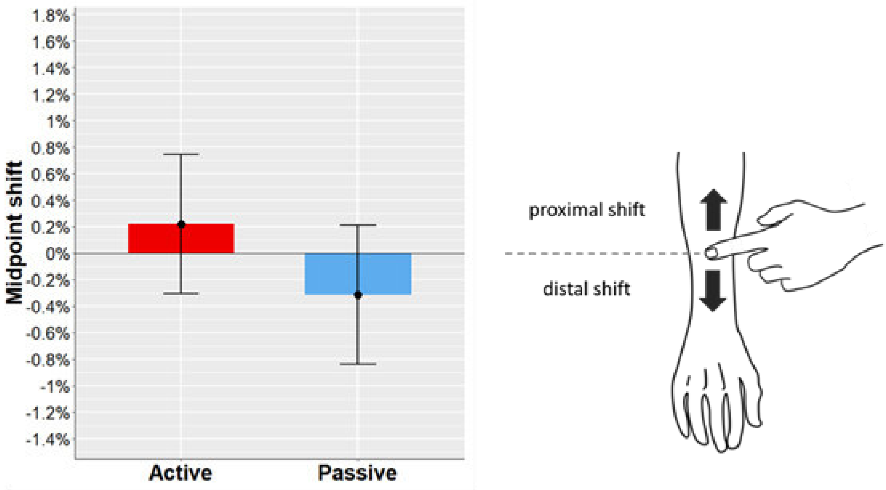


Figure 5. Midpoint shift following MB training. *Bars represent mean differences (± 95% CI) between bisection performance before and after MB training. The shift is reported as percentage of the total forearm and hand length. Negative values reveal a shift towards the hand (distal shift), while positive values indicate a shift towards the elbow (proximal shift). Midpoint displacement for different experimental conditions is depicted. CI were calculated with summarySEwithin function (http://www.cookbook-r.com/Graphs/Plotting_means_and_error_bars_(ggplot2)/).*

showing that essential factors for the arising of subjective sense of ownership are anatomical congruency (Braun et al., 2014; Kalckert & Ehrsson, 2012) and visuomotor synchrony (Dummer et al., 2009; Kalckert & Ehrsson, 2014a; Kalckert & H. Ehrsson, 2017), but not mode of movement (Kalckert & Ehrsson, 2012, 2014a). This finding, which indicates that the sense of ownership for an extracorporeal hand arises regardless of passive or active movement agrees with the phenomenological distinction between voluntary and involuntary actions formally described by Gallagher (Gallagher, 2000).

As for sense of agency, previous accounts suggest that a central factor of modulation is the mode of movement. Passive movement execution almost abolishes sense of agency for the fake hand (Kalckert & Ehrsson, 2012, 2014a). A residual sense of agency was observed for a moving rubber hand in anatomically congruent position, but this finding was interpreted as the tendency to ascribe covert sense of agency for an owned hand as opposed to explicit feeling of motor control elicited by a voluntary movement (Kalckert & Ehrsson, 2012, 2014a). On the other hand, anatomical implausibility (i.e., the dummy hand rotated 180°) as well as temporal incongruency (i.e., the dummy hand finger moved 180° out-of-phase) do not completely disrupt the sense of agency. The sense of agency was observed to emerge both in case of congruent and incongruent posture of the fake hand (Braun et al., 2014; Kalckert & Ehrsson, 2012). Similarly, positive ratings of agency statements were note in conditions of active out-of-synch movements (Kalckert & Ehrsson, 2014a). In this regard, two different type of agency was considered, i.e., *the sense of body agency* and *the sense of external agency*. The sense of body agency is the feeling of control over the extracorporeal body-part-like object able to fulfil skeletomuscular and spatial constraints of the body. Sense of external agency is instead the experience of control over external sensory events (Kalckert & Ehrsson, 2012). In the latter case, the systematic relationships

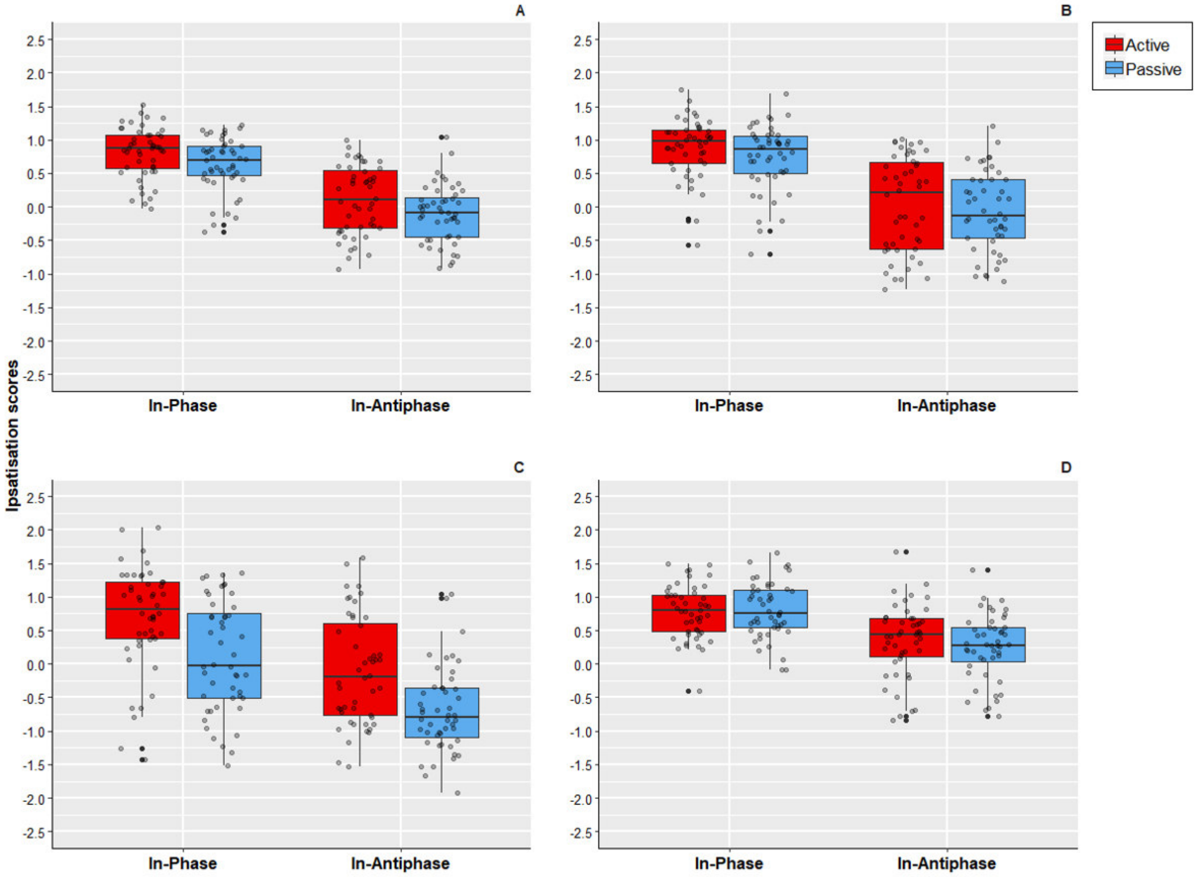


__Figure 6. Box plot of embodiment questionnaire ratings__. The median, two hinges and two whiskers of ipsatised ratings of the Embodiment component (panel A) and its subcomponents Ownership (panel B), Agency (panel C) and Location (panel D) for the four experimental conditions.

between one's motor intention and its consequences in the environment suffice for self-agency attribution. Therefore, the fake hand can be interpreted as an extracorporeal tool that systematically and foreseeably responds to participant's motor commands, even though without perfect isomorphism with his/her hand movements. The current study confirms that both temporal congruency and mode of movement are important aspect for the feeling of agency. As such, sense of agency not only depends on the matching between visuo-proprioceptive afference, but also on the generation of an intention-to-move. Data from the questionnaire hence demonstrate that both temporal incongruency and passive displacement of the finger are effective in significantly reduce the intensity of agency. Overall, this trend in results agrees with previous accounts suggesting that passive movement can abolish the overt experience of agency over the alien hand. It is also in accordance with the fact that an asynchronous feedback can reduce sense of body agency.

As previously done by other studies, we took advantage of the comparison between active and passive movement to verify whether the distal midpoint shift represent an implicit correlate of self-agency. For instance, Haggard, Clark, & Kalogeras (2002) found that intentional binding shows up only when intentionality comes into play (i.e., voluntary key press), whereas perceptual repulsion between movement and consequences occurs in case of externally-induced movement (i.e., involuntary key press induced by TMS). An analogous pattern of intentional binding modulation also emerged when a movement engender a somatic effect, specifically a TMS-induced twitch of the contra-lateral index finger (Tsakiris & Haggard, 2003). Inconclusive results about bisection performance do not support the hypothesis that perceiving sense of agency for the mirrored hand triggers the distal shift of the perceived forearm midpoint. Hence, a strict relationship between these two measures is disconfirmed.

To conclude, the modulation of sense of agency does not seem to be a key factor underlying the bidirectional modulation of bisection performance. Other factors might be implicated, such as visual attention.

3.3 Experiment 1.2

3.3.1.1 Rationale of the study

Experiment 1.1 led inconclusive results about the reason for the bidirectional shift of forearm midpoint. In as much as sense of agency was found to be not relevant in modulating the bisection performance at the group level, other factors should be investigated.

3.3.1.2 Aims

It will be here considered the effect of the allocation of spatial attention towards a certain point in space (i.e., the hand) on the bisection performance. The bidirectional relocation of forearm midpoint across conditions in Experiment 1 disproven this interpretation because if this were the case, a distal midpoint shift would have resulted in all conditions. In fact, participants were required to look at the same position in space across all experimental conditions. However, it has been shown that some tool-mediated effects may be driven by focusing spatial attention resources on the tool tip (Holmes, Calvert, & Spence, 2007; Holmes, Sanabria, Calvert, & Spence, 2007). In an analogous manner, the distal relocation of the forearm midpoint might have been due to attentional processes during MB training. This issue will be here specifically addressed.

3.3.2 Methods

3.3.2.1 Subjects

Forty-eight healthy volunteers (20 males and 28 females; mean age ± s.d.: 22.69 ± 4.28 years; mean educational level: 15.73 years) accepted to participate in the experiment. Almost all the participants were students enrolled by word of mouth and by the online recruitment system of Department of Psychology (University of Milano-Bicocca). The Ethical Committee of the University of Milano-Bicocca approved the study. The study was carried out in accordance with the principles of the Declaration of Helsinki (World Medical Organization, 1996). All participants provided their written informed consent. Students received course credits for their participation.

3.3.2.2 Experimental procedure

The experimental procedure was akin to the that of the Experiment 1 (see 3.2.2.2) and the experimental apparatus was the same as that of the Experiment 1.1 (Figure 4). The current study was designed to control for two explanatory variables, i.e., the *Mode of Movement* (Active Movement *vs.* Passive

Movement)[13] and the occurrence of the *Visual Feedback* (Mirror *vs.* No-Mirror). During each condition (1) Pre-training bisection task, (2) MB training, (3) Post-training bisection task were subsequently administered.

MIRROR BOX TRAINING

The participant was asked to perform index finger movement with the hand behind the mirror while looking at the experiment's hand reflected in the mirror by using the same MB apparatus as in the previous experiment.

The occurrence of the visual feedback was manipulated in two different types of conditions: (1) *Feedback*: the participant performed the task while looking at the mirror in which he/she could see the experimenter's hand moving synchronously; (2) *No-Feedback*: the participant performed the task while looking at the mirror that was in these conditions covert by a black cardboard to prevent visual information; the participant was instructed to look at the covert mirror as if he/she was gazing at his/her hand.

Furthermore, participants performed two types of finger movements: (1) *Active movement*: the participant was to actively press the lever with the hand behind the mirror at their own pace at around approximately 1 Hz; (2) Passive movement: the participants were to leave the finger to be passively moved by the lever. The order of conditions and hand laterality were completely randomized across subjects. Overall, participants underwent four experimental conditions in total.

BISECTION TASK

For a detailed description, see 3.1.2.2.

3.3.2.3 Data analysis

Bisection *R* values were analyzed via linear mixed-effects model - *lmer* function; lme4 package (Bates & Sarkar, 2006). Model selection has been carried out through automatic backward stepwise elimination of the effects introduced in the full model. According to this procedure, random parameters are tested first, then fixed effects are evaluated starting from higher-order interactions. Effects are retained when improve model goodness-of-fit - *step* function; lmerTest package (Kuznetsova et al., 2017). Lastly, a Type III mixed-design ANOVA was performed on the final model.

[13] The comparison between active and passive movement has been here maintained to make results of this experiment more straightforwardly comparable to those of Experiment 1.1.

Fixed Structure	B	df	t-value	*p*	lower CI	upper CI
Intercept	0.702	56.11	100.701	<.001	0.688	0.716
FeedbackNoMirror	0.004	3783	5.173	<.001	0.003	0.007
Random Structure						
σ^2_{ID}	0.002					
σ^2_{Trial}	0.000					
σ^2_{Res}	0.000					
N_{ID}	48					
N_{Trial}	10					
ICC_{ID}						
ICC_{Trial}						

Table 6. Fitted linear mixed model and summary statistics. *The upper part lists the fixed parameters estimates (B) and their associated degree of freedom (df), t-value, 95% CI and p-value. The lower part shows random intercepts' variance (σ^2) and intraclass correlation (ICC).*

3.3.3 Results

The most parsimonious model evaluated by the stepwise backward selection included both random effects and the main effect *Feedback* (Table 7). Analysis of variance run on the final model revealed a significant effect of the main effect *Feedback* [$F_{1,3783} = 26.75$; $p < .001$]. Since no effect of time resulted, no midpoint shift was calculated.

3.3.4 Discussion

Results from this experiment rule out an effect of spatial attention on bisection performance. Based on these results and those of Experiment 1 and Experiment 1.1, the most reasonable conclusion that can be drawn is that the bidirectional midpoint shift might represent an implicit correlate of embodiment during the execution of manual movements, though not straightforwardly related to the agency subcomponent. Further research could be deserved in exploring the relation between body metric task, like the forearm bisection task, and other aspects of visuomotor BOIs, such as sense of ownership.

4 Processes for body awareness in action

The rise of the illusion of embodiment of an alien body part in the context of a visuo-motor BOI is driven by the conjunction of at least two factors: the temporal proximity between visuo-proprioceptive feedback and the occurrence of the intention-to-move. The purpose of the next study is to test which of these two aspects is mostly engaged in compromising the MB illusion in persons with schizophrenia.

4.1 Experiment 2

4.1.1.1 Rationale of the study

Results from Experiment 1 suggested that an abnormal embodiment (as shown by an altered modulation of the sense of agency and bisection performance) might depend on a widened visuo-proprioceptive TBW as well as on the disruption of effective motor predictions. However, whether one or both the mechanisms are critical in the disruption of body perception could not be ascertained.

Based on studies about sense of body agency in patients reviewed in 1.2, both processes might be significantly impaired in schizophrenia. Franck and colleagues systematically investigated the capability to recognize own movement by detecting spatiotemporal distortions in the visual feedback. They found that patients have a less restrictive visuo-proprioceptive mismatch detection threshold (Franck et al., 2001). Findings from other studies corroborated that finding (Daprati et al., 1997; Fourneret et al., 2001; Fourneret et al., 2002; Haggard et al., 2003). On the other hand, studies investigating the sensory attenuation effect (Blakemore et al., 2000; Lindner et al., 2005; Shergill et al., 2005), the predictive and postdictive components of the intentional binding (Voss et al., 2010) and prediction-based perceptual estimates of hand movements (Synofzik et al., 2010) provided evidence for the high unreliability of motor predictions in schizophrenia.

As argued in Experiment 1, both the processes putatively affecting sense of agency in schizophrenia are recruited during the embodiment of an alien hand. Embodying an extracorporeal moving hand involves the integration of visual and somatic (proprioceptive/tactile) reafferent inputs as well as the generation of efferent signals. For instance, temporal contiguity between somatic feedbacks allows sense of ownership during the RHI. On the other hand, the arising of efferent signals paralleling the generation of the motor command (e.g., the internal predictions about motor consequences) are thought to be important for illusorily sense of agency.

Prior experimental evidence suggests that both afference and efference are important sources of body awareness. On the role of efferent signals for body processing, Tsakiris and co-workers showed that they improve the self-recognition of bodily movements since individuals were more accurate in discriminating self-generated movement from other's movement under condition of active rather than passive movements. Contrary to involuntary movements, voluntary movements entail the production of efferent signals (Tsakiris et al., 2005). In this vein, Shimada and colleagues assessed the interplay between the production of efferent signals and the integration of visuo-proprioceptive feedback under condition of active and passive movements. Their results indicate that the presence of efferent signals does not significantly improve the detection threshold for temporal mismatch. However, they found that efferent signals are crucial in enhancing the contrast between synchronous and asynchronous feedbacks. As they reported, "*this is also supported by the post experiment, non-structured interview showing that most subjects were more confident in judging asynchrony in active than in passive movements*" (Shimada, Qi, et al., 2009).

The question remains whether putatively impaired efference and/or visuomotor TBW make a distinctive contribution to embodiment and self-body processing in schizophrenia. Speculatively, it might be that both motor prediction and TBW of cross-modal afference integration jointly impair MB illusion as seen in Experiment 1. As such, the additive effect of unreliable and/or noisy motor predictions together with reduced multisensory temporal resolution of sensory reafference might account for an abnormal embodiment in schizophrenia.

4.1.1.2 Aims

The purpose of Experiment 2 is to investigate whether TBW and/or motor prediction is/are involved in altering body awareness arising from visuo-proprioceptive integration in schizophrenia. To this extent, we sought to separate the distinctive contribution of the two processes on embodiment judgment by comparing (1) active and passive movements and (2) different time-lags between visual and proprioceptive reafferent signals.

The main difference between active and passive movements lies in whether the efferent signals related to motor command are available. Efferent signals pertain those processes preceding the actualization of the movement, i.e., the intention-to-move, the generation of a motor command and the production of sensory predictions. The comparison between active and passive movement, which allows the investigation of sense of ownership with and without the concurrence of sense of agency (see 3.2.3.2), also allows to address the integration of visuo-proprioceptive afferents with and without the production of the efferent signals. In such a way whether efferent signals make a differential contribution to the integration of visuo-proprioceptive afferent inputs serving bodily awareness in schizophrenic patients was explored in the present study. The comparison across several time windows is instead functional to understand the role of multisensory TBW on the MB illusion in the clinical group at issue.

4.1.2 Methods

4.1.2.1 Subjects

Eighteen in- and out-patients with a diagnosis of schizophrenia at Bolzano Hospital Mental Health department, at Milan Santi Paolo e Carlo Hospital Mental Health department and their community services have been involved in the study. All patients met the DSM-IV criteria for schizophrenia and were receiving stable dose of antipsychotic medications. Severity of psychopathological symptoms at the time of testing was assessed through the Scale for the Assessment of Negative Symptoms and the Scale for the Assessment of Positive Symptoms (N. Andreasen, 1984; N. C. Andreasen, 1989). Thirty-two healthy participants were recruited by word of mouth or by the online recruitment system of Department of Psychology (University of Milano-Bicocca). Students received course credits for their participation.

The Ethical Committee of the University of Milano-Bicocca and of Bolzano Hospital approved the conduct of the study in abovementioned medical facilities. The study was carried out in accordance with the principles of the Declaration of Helsinki (World Medical Organization, 1996). All participants signed written informed consent.

4.1.2.2 Experimental procedure

The experimental procedure adopted here was basically equal to that of previous experiments. As in previous studies, participants were invited to take their bracelets, rings and watch off before the experiment started and to keep the forearm of the limb under test as still as possible as they could move it after the end of each experimental condition. The study was carried out by two experimenters. The first experimenter played the role of the "alien hand", while the second experimenter administered the questionnaire and coordinated the whole experiment giving instructions to participants and timing the duration of the MB training.

Overall, eight conditions were administered in accordance to the following 2 × 4 factorial design: *Mode of Movement* (Active, Passive) × *Time-lag* (120 ms, 220, ms, 320 ms, 420 ms). To reduce fatigue and/or boredom, the study was split into two sessions (Active Session and Passive Session), each one lasting around 25-30 minutes, with a pause of 10-15 minutes between them.

	SCZ (*n* = 18)	CTR (*n* = 32)
Age, Years	42.67(11.67)	26.72 (9.78)
Sex, Male/Female	16/2	12/20
Handedness, Right/Left/Ambidextrous	15/3/0	27/5
Education, Years	12,11 (2.82)	16.88 (2.31)
SANS		
Affective flattening	NA	–
Alogia	NA	–
Avolition - Apathy	NA	–
Anhedonia - Asociality	NA	–
Attention	NA	–
SAPS		
Hallucinations	NA	–
Delusions	NA	–
Bizarre behavior	NA	–
Formal thought disorders	NA	–
Antipsychotic medication		
First Generation	NA	–
Second Generation	NA	–
Both	NA	–

Table 7. Sample demographics*. Values are presented as n or mean (SD). CTR, healthy controls; SCZ, schizophrenic patients; SANS, Scale for the Assessment of Negative Symptoms; SAPS, Scale for the Assessment of Positive Symptoms.*

MIRROR BOX TRAINING

As in previous studies, the participant was asked to perform index finger movement with the hand behind the mirror while looking at the experiment's hand in the mirror. For the current study, a double-lever electromechanical device was implemented to control for visuo-proprioceptive congruency. The two levers are connected in a way that a lever (the master lever) controls the actuation of the other lever (the slave lever), meaning that when the master slave is pushed, its movement is transmitted to the slave lever, that simulates the rotation of the first one. The intrinsic delay of the apparatus is 40±20 ms. Given this architecture, the participant was in control of the master lever during the active session, whereas during the passive session she/he was to rest his/her finger onto the slave lever that was controlled by the experiment hand from in front of the mirror through the master lever (Figure 7).

In order participants became accustomed to correctly push the lever for the active session, they were invited to practise the movements at the very beginning of the session. To reduce cutaneous input due to the rubbing of the fingertip against the surface of the lever, the pad was stuck to the lever by a little piece of double-sided adhesive tape. Four different delays were imposed between the onset of actuation of the two levers in order to manipulate the time-lag between (alien) visual and proprioceptive feedbacks about the hand. Participants are exposed to 1 minute of stimulation per condition. Partial counterbalancing (*Latin square design*) of the order of presentation of time-lags was used to minimize carryover effect. Moreover, half of the participants were tested on the right hand, while the other half on the left hand.

SELF-REPORT

After each MB condition, participants completed a 16-item questionnaire assessing the subjective embodiment sensations during the visuomotor stimulation. Statements were translated in Italian and partially adjusted from the embodiment questionnaire used in a previous study (Kalckert & Ehrsson, 2012). Half of the items of the questionnaire focuses on sense of ownership (4 items) and sense of agency (4 items) sensations; the remaining part of the questionnaire includes control statements consisting in illusion-like statements which cannot however be ascribed to sense of ownership and sense of agency as they do not properly capture the phenomenological experience under investigation. For the questionnaire translation used in the current study, see Appendix 2.

All the questionnaire items were read to participants and explained if needed. Participant reported their agreement/disagreement with each statement by referring to a 7-point Likert scale presented on a sheet of paper (+3: strong agreement; 0: neither agreement nor disagreement; -3: strong disagreement).

As in previous studies, responses were standardized within-subject to exclude participants' response style effect [*Ipsatisation:* $y' = (x - mean_{individual})/SD_{individual}$] (Fischer & L. Milfont, 2010). The average score of embodiment components assessed through questionnaire - *Ownership, Agency, Ownership-control, Agency-control* - were calculated and submitted to statistical analyses.

4.1.2.3 Data analysis

Questionnaire scores relating to each component were assessed for normal distribution of residuals. Since at least one of the subgroups of data failed to meet the assumption of normality within each component dataset, a non-parametric test for factorial designs has been here used – the *Aligned Rank Transformation test*; ARTool package. ART test is appropriate for multi-factors within-subject designs

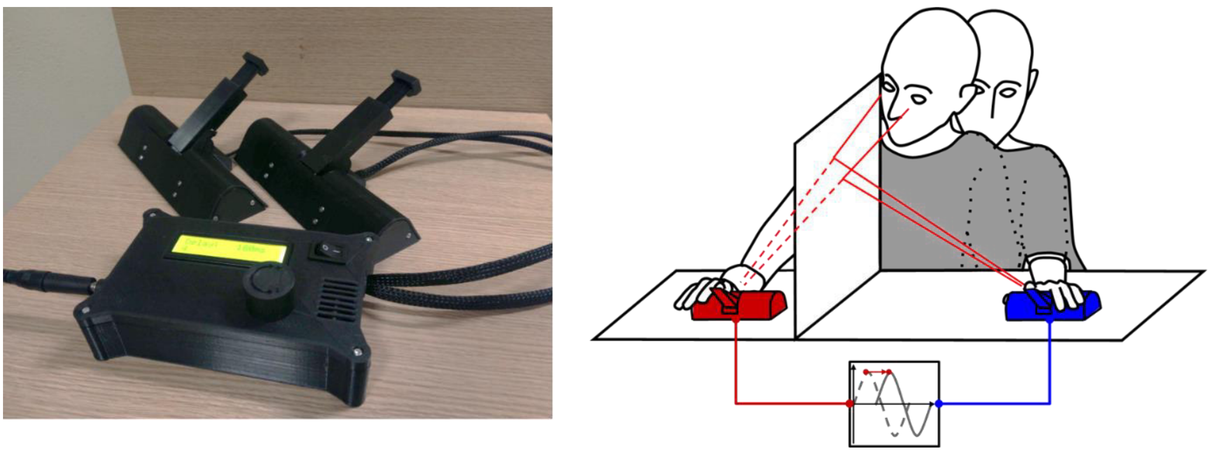


Figure 7. Double-lever electromechanical device. *Left panel: Each lever is made with a plastic bar that can move 30 degrees about a fixed pivot. By an electronic control system, delays of different length can be applied on the onset of actuation of the rotor controlling the slave lever. Right panel: Example of active condition. The participant presses the master red (depicted in red), meanwhile the experimenter places his hand on the slave lever (in blue). In passive conditions the positioning of the levers was inverted.*

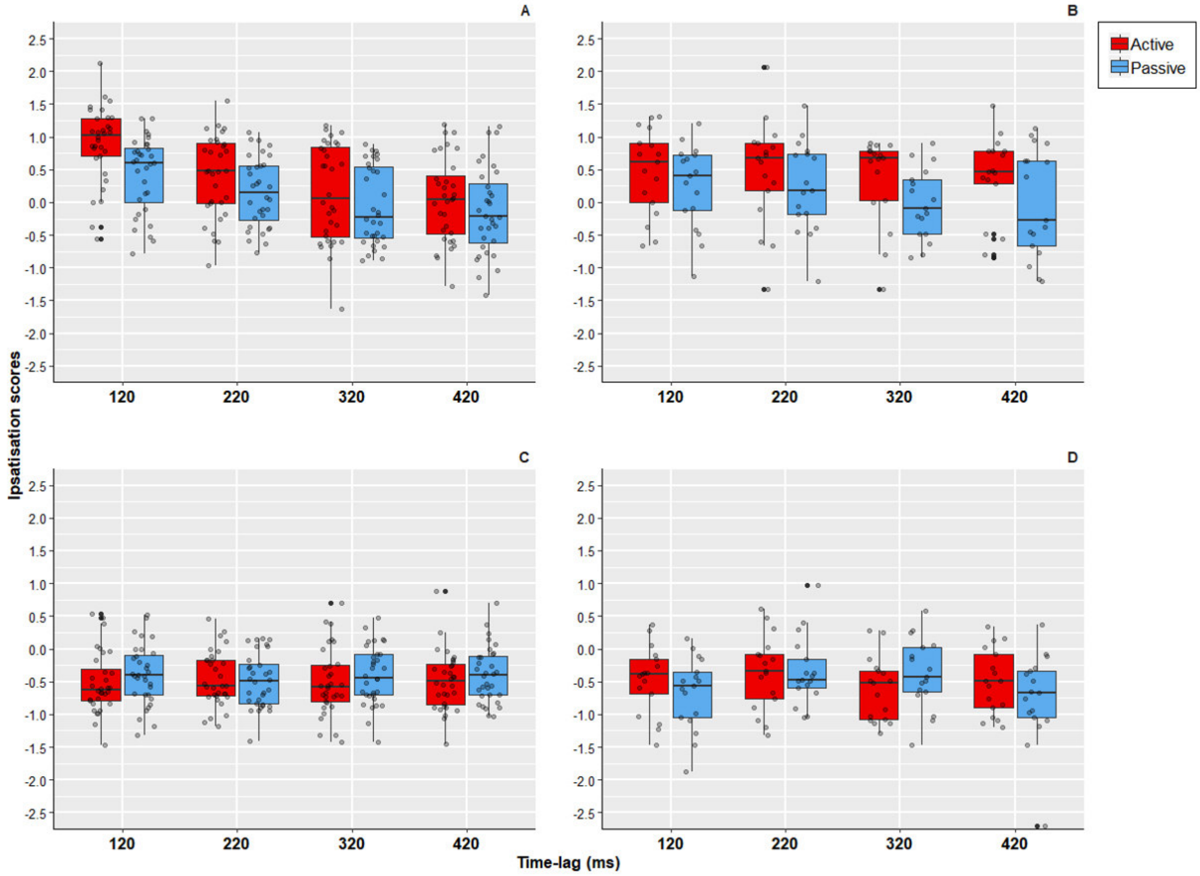


*Figure 8. **Box plot of embodiment questionnaire ratings**. The median, two hinges and two whiskers of ipsatised data. Upper row: Ownership component in controls (panel A) and patients (panel B). Lower row: Ownership-control component in controls (panel C) and patients (panel D). The horizontal axis shows the four time-lags. Red and blue boxplots illustrate active and passive conditions.*

(Kay & Wobbrock, 2019; Wobbrock et al., 2011). All data analyses were carried out with R 1.1.463 (R Core Team, 2019). The variable *Group*, *Time-lag* and *Mode of Movement* were entered as predictors; the variable Subject was also added as error term in the formula to account for the repeated-measure design.

4.1.3 Results

Since data collection is still in process, preliminary results and tentative interpretations are reported below.

Ownership: the main effects *Mode of Movement* [$F_{1,329} = 29.129$; $p < .001$; $\eta_p^2 = .08$] and *Time-lag* [$F_{3,329} = 19.267$; $p < .001$; $\eta_p^2 = .15$] and the two-way interaction *Group* × *Time-lag* [$F_{3,329} = 4.188$; $p = .006$; $\eta_p^2 = .037$] were significant. All other effects of *Group* [$F_{1,47} = 0.175$; $p = .677$; $\eta_p^2 = .004$], *Group* × *Mode of Movement* [$F_{1,329} = 0.098$; $p = .755$; $\eta_p^2 = .00$], *Mode of Movement* × *Time-lag* [$F_{3,329} = 0.298$; $p = .827$; $\eta_p^2 = .002$] and *Group* × *Mode of Movement* × *Time-lag* [$F_{3,329} = 0.819$; $p = .484$; $\eta_p^2 = .007$] were not. As such, subjective sense of ownership is significantly boosted by the performance of a

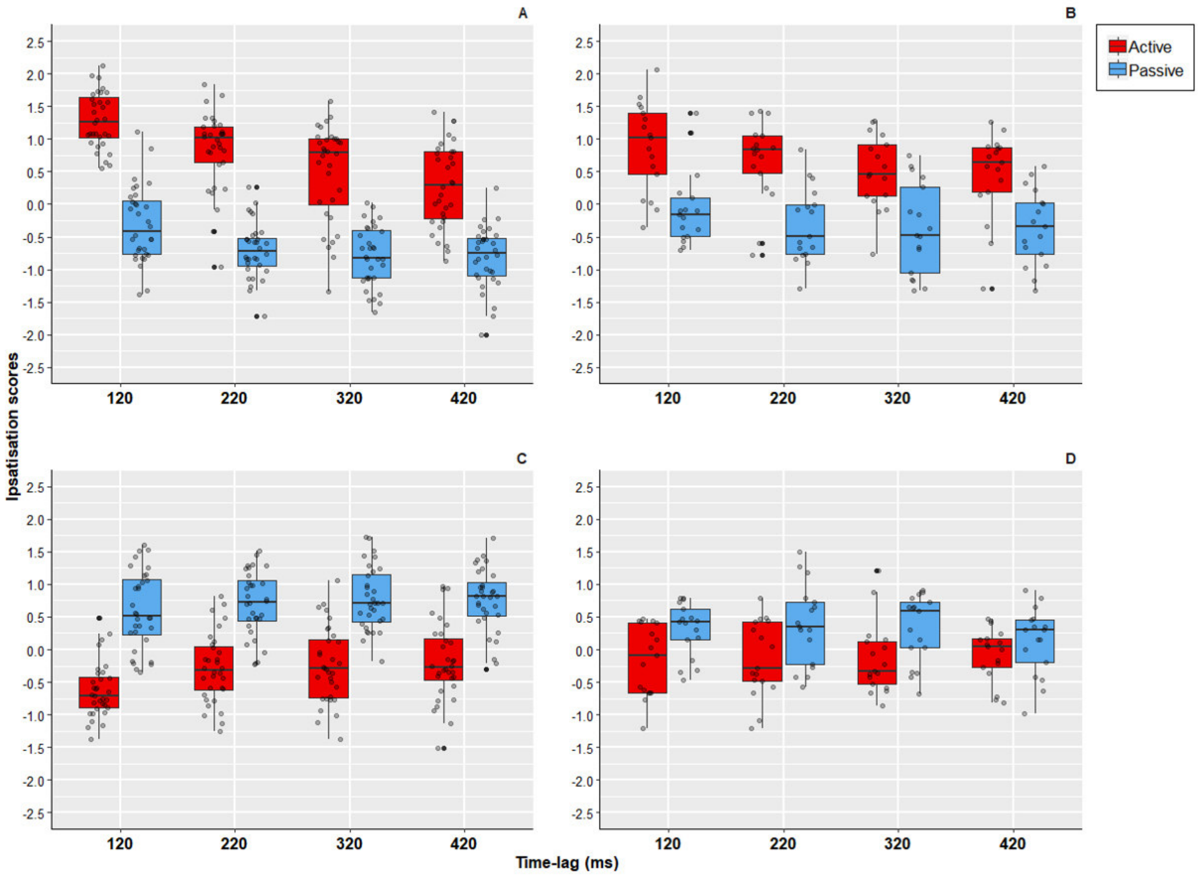


Figure 9. Box plot of embodiment questionnaire ratings*. The median, two hinges and two whiskers of ipsatised data. Upper row: Agency component in controls (panel A) and patients (panel B). Lower row: Agency-control component in controls (panel C) and patients (panel D). The horizontal axis shows the four time-lags. Red and blue boxplots illustrate active and passive conditions.*

voluntary action and it is driven by the temporal contiguity between visuo-proprioceptive information in both groups. In addition, the interaction group by time-lag indicates that sense of ownership is reduced by the increase in visuo-proprioceptive asynchrony in healthy controls, while it seems to be less dependent on time-lag in the schizophrenia group (Figure 8 - panel A and B).

Ownership-control: as concerns this questionnaire component, none of the effects was significant, as follows: *Group* [$F_{1,47}$ = .132; p = .718; η_p^2 = .003], *Mode of Movement* [$F_{1,329}$ = 1.42; p = .234; η_p^2 = .004], *Time-lag* [$F_{3,329}$ = 0.654; p = .581; η_p^2 = .006], *Group* × *Mode of Movement* [$F_{1,329}$ = 1.862; p = .173; η_p^2 = .006], *Group* × *Time-lag* [$F_{3,329}$ = 1.761; p = .155; η_p^2 = .02], *Mode of Movement* × *Time-lag* [$F_{3,329}$ = 1.567; p = .197; η_p^2 = .01] and *Group* × *Mode of Movement* × *Time-lag* [$F_{3,329}$ = 1.879; p = .133; η_p^2 = .017]. As such, unlikely sensations of ownership (e.g., having more than one hand), if present, are not subject to conditional manipulations of the experiment.

Agency: interaction effects *Group* × *Mode of Movement* [$F_{1,329}$ = 16.152; p < .001; η_p^2 = .05] and *Mode of Movement* × *Time-lag* [$F_{3,329}$ = 3.243; p = .022; η_p^2 = .029] were significant and the effect *Group* × *Time-lag* [$F_{3,329}$ = 2.579; p = .054; η_p^2 = .02] was marginally significant. In addition, the main effects *Mode of Movement* [$F_{1,329}$ = 579.086; p < .001; η_p^2 = .636] and *Time-lag* [$F_{3,329}$ = 24.433; p < .001; η_p^2

= .182]. The effects of *Group* [$F_{1,47}$ = 1.762; p = .191; η_p^2 = .04] and *Group* × *Mode of Movement* × *Time-lag* [$F_{3,329}$ = 0.506; p = .679; η_p^2 = .005] were instead not significant. This latter result is indicative of a broadly similar trend of modulation between groups. Accordingly, higher visuomotor temporal incongruencies and passive movements reduce the intensity of sense of agency. Nonetheless, the two-way interactions suggest that the differences in subjective agency driven by the two factors are less strong in the schizophrenia group (Figure 9 – panel A and B).

Agency-control: the two-way interaction effect of *Group* × *Mode of Movement* [$F_{1,329}$ = 42.767; p < .001; η_p^2 = .12] was significant together with the main effects *Mode of Movement* [$F_{1,329}$ = 364.631; p < .001; η_p^2 = .526] and *Time-lag* [$F_{3,329}$ = 3.826; p = .01; η_p^2 = .034]. Conversely, the effects of *Group* × *Time-lag* [$F_{3,329}$ = 2.444; p = .064; η_p^2 = .022], *Group* [$F_{1,47}$ = 0.794; p = .377; η_p^2 = .02], *Mode of Movement* × *Time-lag* [$F_{3,329}$ = 1.432; p =.233; η_p^2 = .01] and *Group* × *Mode of Movement* × *Time-lag* [$F_{3,329}$ = 0.657; p = .579; η_p^2 = .005] were not significant. Thus, weird sensations of control (eg. passivity-like sensations like the sense that the veridical hand is controlled by the alien hand; or unlikely sensations like sensing movements in the space between own hand location and the location of the mirrored hand) modulate similarly between groups, though differences induces by mode of movement are attenuated in the clinical group.

4.1.4 Discussion

Consistent evidence from BOIs suggest that multisensory synchrony is pivotal for self-body processing (Kilteni et al., 2015). As regards the specific case of visuomotor BOIs, evidence from the "robot hand illusion" indicates that visual feedback delays lower than 200 milliseconds are necessary for self-body processing. This visuomotor variant of BOI has been systematically investigated with respect to visual feedback delays ranging from 90 milliseconds to 590 milliseconds. Sense of agency and sense of ownership more strongly arise under delays smaller than 200 milliseconds (Ismail & Shimada, 2016). As regards schizophrenia, results by Franck et al. (2001) are suggestive of an enlarged visuo-proprioceptive TBW. In that study, participants were to recognize their own movements from others' movements based on a virtual feedback. It was found that patients with delusions of influence were less able to detect the spatial visuo-proprioceptive conflict because they self-attributed visual feedback up to 30° of distortion, whereas control participants and non-influenced patients became aware of the spatial bias around 15°. Besides, the overall schizophrenia group kept on self-attributing distorted movement up to 300 milliseconds delays compared to 150 milliseconds in the control group.

These studies as well as Experiment 1 did not disentangle the distinctive contribution of efferent and afferent signals to self-body processing. For this reason, the current study aimed at dissociating efference-related phenomena (motor intention, motor prediction and comparative processes) and an afference-related phenomenon (multisensory integration of visuo-proprioceptive reafference) by controlling for mode of movement and cross-modal temporal delays.

The significant interaction *Mode of Movement* by *Time-lag* regarding sense of agency modulation is in accord with results from Experiment 1.1. and previous studies on "active RHI" (Braun et al., 2014; Kalckert & Ehrsson, 2012, 2014a), supporting the hypothesis that for sense of agency to arise temporal correlation between afferent feedback is necessary but not sufficient because it has to be complemented by efference-related processes allowed by the execution of a willed movement. Specifically, current results indicate that sense of agency decreases with increasing visuo-proprioceptive discrepancy, though differences driven by cross-modal mismatch are substantially smoothed out by the passive mode of movement. As can be seen in graph (Figure 8, upper panels), this effect in agency modulation is generally present in both groups.

Despite the globally similar trend of sense of agency between groups, *Mode of Movement* and *Time-lag* are both differently modulated by the factor *Group*. Indeed, the sense of agency in the schizophrenic group turns out to be reduced to a lesser extent by the visuo-proprioceptive asynchrony. In addition, the difference in sense of agency between an active and passive movement is remarkably attenuated with respect to healthy participants. These results partially replicate those of a very recent study about sense of agency in schizophrenia patients tested by the visuomotor version of the projected hand illusion[14]. In this study, patients display to perceive voluntary movements more akin to involuntary ones. The abnormal modulation of agency sensations involves specifically patients with passivity profile. Moreover, it is confined to items assessing the presence or absence of "*agency over own hand*"[15]. In contrast, also patients with no history of passivity symptoms show a smaller and not significant reduction of agency over the projected-hand" in the asynchronous condition (i.e., 500 ms delay). As authors suggest, a deficit in proprioceptive prediction, responsible for the disruption of sensorimotor processes underlying pre-reflective feeling of agency, would engender the abnormal judgment of agency over own hand (see 1.2 for the distinction between feeling of agency and judgment of agency) demonstrated by patients with passivity. Conversely, a widened TBW would be a common deficit of patients with schizophrenia (Graham-Schmidt, Martin-Iverson, & Waters, 2018).

As in the just mentioned study, the overt awareness of executing an active or a passive movement with the lever (given that participants were explicitly instructed to the movements they had to carried out) does not induce strongly different intensities of agency over the alien hand inpatients. In a similar vein, the poor sensitivity to visuo-proprioceptive discrepancies make patients to show an

[14] This study adopted the same equipment and questionnaire previously used to test the visuo-tactile version of the illusion in schizophrenic patients with passivity profile (Graham et al., 2014) (see Table 2).

[15] Unlike the present study, Graham and colleagues distinguish between "agency over own veridical hand" compared to "agency over the video-projected hand". Broadly speaking, our agency statements resemble items pertaining to "*agency over the video-projected hand*", whereas agency-control statements may represent a mixture of items about "*loss of agency over own hand*" and "*loss of agency over the video-projected hand*".

attenuated modulation of agency self-reports, irrespective of the mode of movement. Therefore, these provisional results reveal that both efference- and afference-related processes provide patients with altered cues for self-body agency.

Over the last decade, several studies adopting the visuomotor variant of the RHI have addressed whether the generation of efferent signals has a promoting effect on sense of ownership in embodiment. On the implicit ground, efference was found to qualitatively modify the proprioceptive perception by making body percept from fragmented to cohesive and unified, as demonstrated by a "global" proprioceptive drift (Tsakiris et al., 2006). As regards subjective experience, some accounts support the view that efference heightens sense of ownership (Braun et al., 2014; Dummer et al., 2009), whereas other accounts suggest that it neither strengthens (Kalckert & Ehrsson, 2012, 2014a) nor so fundamentally catalyses the onset of the illusion (Kalckert & H. Ehrsson, 2017). According to this latter line of research, the relationship between agency and ownership may be even "reversed", i.e., sense of ownership facilitates sense of agency (Kalckert & Ehrsson, 2014a). As suggested by a recent review, the inconsistency of results may indicate that the interplay between sense of ownership and sense of agency is bidirectional more than unidirectional. Therefore, when they co-occur, they may strengthened each other (Braun et al., 2018). In this regard, the strongly significant modulation of sense of ownership by *Mode of Movement* found in the current study supports the former view suggesting that the execution of an active movement enhances the vividness of sense of ownership (see Figure 8, upper panels). Accordingly, the synchrony between visual and proprioceptive inputs suffices for the illusion of ownership, but this latter can be enhanced by sense of agency.

Importantly, *Mode of Movement* effect emerges irrespective of the *Group* factor, suggesting that disrupted efferent signals in visuomotor integration might not be so critical in altering the subjective feelings of ownership in schizophrenia. Conversely, the interaction effect *Group* by *Time-lag* suggests that sense of ownership referred by patients results to be more strongly affected by a general insensitivity to visuo-proprioceptive temporal mismatch. Beyond reaffirming an abnormal internal timing for multisensory events (Foucher, Lacambre, Pham, Giersch, & Elliott, 2007; for a recent review: Zhou et al., 2018), this finding points to a TBW deficit affecting sense of ownership irrespective of the type of movement to be performed in schizophrenia. Based on this provisional finding, it might be speculatively concluded that an enlarged visuo-proprioceptive TBW more than an impairment of efference (and its related processes) influences body ownership during action.

As explained in 1.2, an explicit judgment of agency differs from the implicit pre-reflective feeling of agency. The former does not only rely on sensorimotor cues, but also on contextual cues and higher-order cognitive factors and personal understanding of the situation. A limitation of the study is the lack of a feasible objective measure of the phenomena under investigation to support finding from the questionnaire. To limit this issue, we explained the functioning of the setup at the end of the experiment. Moreover, before administering the questionnaire we invited participants to respond by referring as much as possible to their perceptual experience of the event.

Unfortunately, unbalanced comparisons by group make this ad interim interpretation of results still inconclusive. The final conclusions will be drawn at the end of data collection, also in the light of psychopathological data.

5 Spatial limits of body ownership

In order to investigate the malleability of body representation in schizophrenia, spatial constraints of the illusion could be addressed. The purpose of the next study is to test whether sense of ownership during the MB illusion decays at higher degrees of spatial incongruency between the visual and the proprioceptive information in a sample of healthy people.

5.1 Experiment 3

5.1.1.1 Rationale of the study

Based on the strong RHI vividness in patients with schizophrenia and on the anecdotal observation they start experiencing the illusion even before the multisensory stimulation, Thakkar et al. (2011) suggested that patients might have a more flexible and weaker internal body representation. In a similar fashion, a recent review on the topic puts forward the hypothesis that the higher susceptibility to the illusion would depend on a stronger reliance on multisensory information over potentially weaker stored body representation (Klaver & Dijkerman, 2016).

In order to test the malleability of internal body representation in schizophrenia, it could be investigated whether patients are more prone than healthy participants to embody extra-personal limb that overtly violates anatomical and spatial constraints of body schema. In fact, "*We do not tend to mistake a hand over the other side of the room as our own just because it looks like a hand. Intuitively, in order to feel like a seen hand is part of our body, it needs to be spatially close to us*." (Preston, 2013; p. 178). In this regard, the peri-personal space may play a role in that it may represent a boundary zone functional, not only to reaching or defensive behaviour, but also to self-attribution of bodily signals, i.e., *self-body ownership* (Makin et al., 2008).

Since little information is available about spatial rules of visuo-motor BOI in neurologically and psychiatrically unimpaired population, an exploratory investigation, using the MB procedure previously explained, has been carried out first. This study is preliminary to a future experiment aimed at investigating whether a patient with schizophrenia is prone to embody extracorporeal hand that eminently violate basic anatomic constraints and, in turn, peri-personal space limits.

5.1.1.2 Aims

Few prior studies systematically addressed the spatial limits of the RHI (Kalckert & Ehrsson, 2014b; Lloyd, 2007; Preston, 2013; Zopf, Savage, & Williams, 2010). A brief summary of them is provided below.

With the aim at quantifying the boundaries of peri-hand multisensory space, Llyod first tested the strength of the illusion for increasing distances between the veridical hand and the dummy hand. She found that when the fake hand was placed more than 27.5 cm away from the participant's own hand, the illusion starts decaying. Since the illusion is likely to persists as long as visual stimuli fall within visual receptive field around participant's hand being touched (Makin et al., 2008), that result was interpreted as the spatial extent of the representation of the peri-hand space (Lloyd, 2007). Nonetheless, the fake hand was positioned further away from the real hand but also increasingly rotated toward participant's body; as such, the confounding effect of postural incongruency may have accounted for the reduction of RHI (Lloyd, 2007; Makin et al., 2008). Therefore, a following study modulated the lateral distance of the fake hand without introducing postural confounds. The rubber hand was kept on a constant location in front of the subject while the participant's hand was laterally shifted 15 cm and 45 cm away from it. At the closer distance, RHI was high regardless of the synchrony of stimulation. At the larger distance, RHI decreases in case of asynchronous stimulation. As authors suggested, a fake hand within peri-hand space triggers multisensory integration regardless of temporal congruency, however a fake hand outside peri-hand space boundaries can be embodied in case of multisensory temporal congruency. For this reason, synchronous stimulation would be able to expand peri-personal space anchored to the hand (Zopf et al., 2010). Nonetheless, Preston argued that the lack of modulation between the two conditions of synchronous stimulation relies on the fact that the fake hand moved outside the peri-hand, but always staying within peri-personal space. In her view, a further factor should have been controlled for, that is the distance from the body midline. In her experiment, she hence modulated (a) the position of the dummy hand with reference to the proximity to the trunk and (b) the position of the real hand with respect to each chosen position of the dummy hand. Questionnaire data showed that the illusion decreases as an effect of distance when the real hand is near the body and the fake hand is far away from the real hand but also from the body midline. This indicated that peri-personal space boundaries matters for RHI to emerge (Preston, 2013).

One experiment specifically addressed the effect of distance on the active RHI (i.e., the motor version of the RHI in which a fake hand synchronously or asynchronously moves with respect to participant's hand). In this study, the fake hand was placed at three different distances from the real hand: 12 cm, 27.5 cm and 43 cm. The illusorily sense of ownership was observed to significantly decline at 27.5 and 43 cm. The decline of the illusion was partially different to that in the visuo-tactile version of RHI, which significantly decreased in intensity only at 43 cm (Kalckert & Ehrsson, 2014b). This was said to indicate a narrower spatial rule for the visuo-motor version of the RHI, which was speculatively interpreted as an effect of the shrinkage of the spatial window of visuo-somatic information integration due to the presence of efferent information. Nevertheless, the distance between the fake and the real hand was modified along the vertical plan in front of the participant, i.e., moving away from the peri-hand space only. Hence, this account does not provide information on the trend of a visuomotor illusion relative to body midline and peri-personal space.

The purpose of this investigation is to delve into the relationship between sense of ownership and peri-personal space boundaries while sensorimotor integration for body processing is engaged. In particular, the present study set out to explore whether the MB illusion becomes weaker when the mirrored hand gradually moves towards the extra-personal space in the horizontal plane. To this end, the experimenter's hand was increasingly shifted away from the mirror up to a large spatial displacement of the mirrored hand in the mirror from the trunk of the subject. Three different measures of the illusion were collected. First, introspective reports from the subjects. In this regard, a reduction in ratings was expected when the participant saw the mirrored hand far away from the trunk in an anatomically implausible location (i.e., towards the limits of the peri-personal space). Second measure taken was the static proprioceptive drift. Based on Kalckert & Ehrsson (2014b), we predict that a reduction in the magnitude of the perceptual shift at the larger spatial distance. Third, anticipatory Skin Conductance Response (SCR) to incoming noxious somatosensory stimuli. Experimental evidence from patients suffering from somatoparaphrenia[16] shows that the pathological denial of ownership for one's own body limb is accompanied by a reduction in the galvanic response to noxious stimuli (Romano, Gandola, Bottini, & Maravita, 2014). As such, we predicted a reduction in anticipatory SCR to noxious stimuli when the mirrored hand, placed further away from the body, is no more embodied.

5.1.2 Methods

5.1.2.1 Subjects

Thirty-eight healthy participants were recruited by word of mouth or by the online recruitment system of Department of Psychology (University of Milano-Bicocca). Students received course credits for their

[16] A neurological syndrome associated with dis-ownership of the contra-lesional upper limb generally following a lesion of the right parietal cortex. The alien limb can be attributed to another person (Romano & Maravita, 2019; Vallar & Ronchi, 2009).

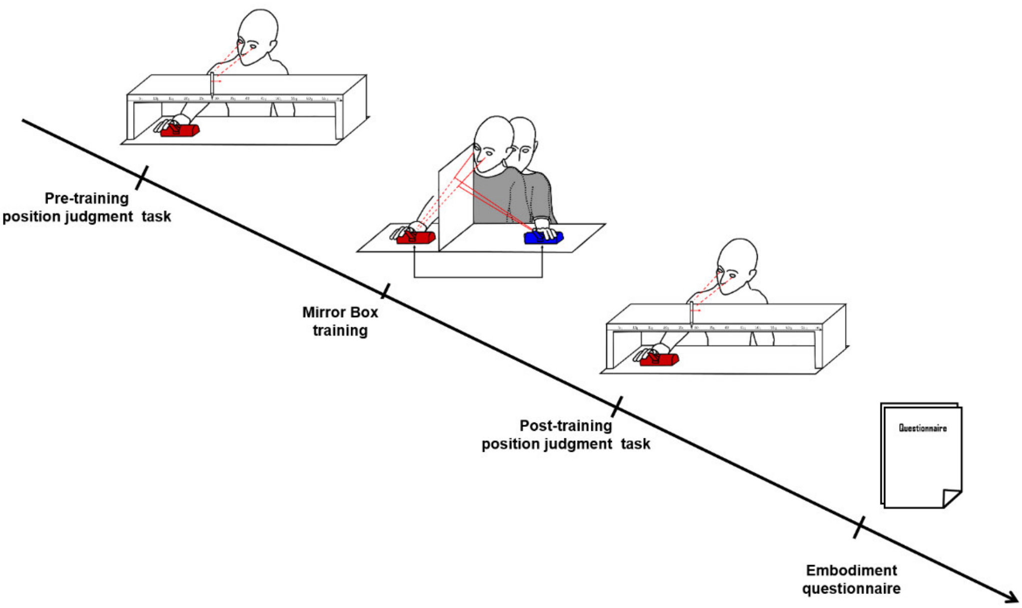


Figure 10. Experimental procedure. *The experimental procedure was repeated in three times in order to vary the extent of visuo-proprioceptive spatial congruency experienced during the MB training. The mirror reflection, which provides the image of an extra-personal limb located in three different location onto the horizontal plane, i.e., close to the body midline, almost overlaying the real hand (10 cm) and gradually far away from body midline towards the extra-personal space (40 cm and 70 cm). The proprioceptive reafference remained constant across conditions as participant's hand stays in the same position across conditions, whereas the visual feedback could be from spatially congruent to incongruent with participant's hand location. Questionnaire statements aimed at assessing the explicit component of embodiment. Perceptual judgment task instead aimed at probing the perceptual remapping of perceived hand location after embodiment.*

participation. The Ethical Committee of the University of Milano-Bicocca approved the study. The study was conducted in accordance with the ethical standards of the Declaration of Helsinki (World Medical Organization, 1996).

All participants gave their informed consent to participate prior to beginning the experiment.

5.1.2.2 Experimental procedure

In this study, participants underwent three experimental conditions of MB training, each one including four phases (Figure 10): (1) the pre-training position judgment task, (2) the MB training, (3) the post-training position judgment task and (4) the embodiment questionnaire. Furthermore, during the MB training skin conductance response to noxious stimuli administered to the hand under illusion was measured from the non-stimulated hand.

As in previous studies, participants were invited to take their bracelets, rings and watch off before the experiment started and to keep the forearm of the limb under test as still as possible as they could move it after the end of each experimental condition. The study was carried out by two experimenters. The first experimenter played the role of the "alien hand", while the second experimenter administered the questionnaire and coordinated the whole experiment giving instructions to participants, applying nociceptive stimulation and timing the duration of the MB training.

MIRROR BOX TRAINING

As in previous studies, the participant closed his/her eyes while the mirror was positioned vertically on the table in a way it was parallel to participant's midsagittal plane and his/her limb was behind the reflective surface. The second experimenter placed his limb on the table in front of the mirror. A black cloth was draped onto participants' trunk and experimenter's forearm to reduce visual interference due to the anatomical implausibility of the experimenter's limb. The position of experimenter's hand in front of the mirror was changed across conditions to obtain different degrees of spatial overlapping between the hand of the participant behind the mirror and the illusory position of the hand reflected in the mirror (*Spatial shift*: 10 cm, 40 cm, 70 cm). Each condition was around four minutes long. The order of presentation of spatial shifts was partially counterbalanced (*Latin square design*) across subjects to control for serial order carryover effect. In addition, the side of the tested hand (right *vs.* left) was balanced across subjects.

The same double-lever electromechanical device of Experiment 2 was used (see 4.1.2.2 for a detailed description). The task of participants consisted in pressing and releasing the master lever behind the mirror while looking at the experimenter hand in the mirror (using the slave lever). Apart from the intrinsic delay of the lever system, no additional delay was introduced. The alien hand thus appears to move in high synchrony with respect to participants hand. Subjects had to push the lever approximately once a second, finding their own internal rhythm. In order they became accustomed to the lever functioning, they were invited to practise the movements at the very beginning of the experiment. To reduce cutaneous input due to the rubbing of the fingertip against the surface of the lever, the pad was stuck to the lever by a little piece of double-sided adhesive tape.

SKIN CONDUCTANCE RESPONSE

During each MB training the experimenter delivered noxious stimuli to the hand of the participant and the mirrored hand with a needle simultaneously. A series of eight stimuli per condition, divided into two separate blocks, were presented to participants. Roughly 30 seconds elapsed between consecutive stimuli. Two types of stimuli were administered, i.e., "contact" stimuli (the experimenter approached and pricked hands with the needle) and "no-contact" stimuli (the experimenter approached hands but stopped at approximately .5 cm from the skin). Contact stimuli were pseudo-randomly introduced between no-contact stimuli to control for SCR adaptation. Besides, the order of stimuli was counterbalanced across subjects. Overall, 24 noxious stimuli per subject were delivered, i.e., 8 stimuli × 3 spatial shifts (10cm, 40cm, 70cm). The eight stimuli administered within each condition were divided into two blocks of four stimuli interleaved by 30 seconds in order to further control for habituation.

SCR was acquired through the amplifier unit GSR100C of the BIOPAC device (BIOPAC Systems, Inc., Goleta, CA, USA). Signal was recorder with two Ag/AgCl (TSD203, Biopac Systems, Inc.)

electrodes fixed on the distant phalanx of the index and middle fingers of the hand not involved in the MB training. Fingertip skin under the sensor was scrubbed and saline conductor gel was locally applied to increase the signal-to-noise ratio. Signal was samples at 200 Hz, low-pass filtered at 10 Hz and acquired with a gain equal to 5 µmho/V.

Pre-processing of data was performed with BIOPAC AcqKnowledge v. 4.2.0 software (Mindware Technologies LTD, Gahanna, OH, USA). Smoothing (factor: 100 samples) and high-pass filter at .05 Hz were applied on the continuous record. Data occurring 10 ms after the markers manually added by the experimenter during the administration were selected. Similar to earlier studies (Armel & Ramachandran, 2003; Llorens et al., 2017; Ma & Hommel, 2013; Palomo et al., 2018; Reinersmann et al., 2013), two participants showing maximum amplitude value lower than .03 µS in all trials (24 out of 24), or almost all trials (23 out of 24), were scored as non-responders and excluded from subsequent analyses. Phasic response to experimental stimuli was then quantified as the peak-to-peak amplitude value within each selected epoch. Peak-to-peak values higher than 2 SD from within-subject mean were scored as statistical outliers (Forgiarini, Gallucci, & Maravita, 2011) and removed from data.

POSITION JUDGMENT TASK

This task consisted in providing proprioceptive estimations of their own index finger position. The task was performed before and after each MB illusion induction. A black wooden board raised by wooden struts was arranged in front of the participant in order to conceal his/her hand from view. Care was taken to avoid participants achieved positional cues from the view of their real hand immediately before the task; thus, they were asked to close their eyes until the apparatus was correctly placed in front of them. For the estimation, the experimenter swiped a paint brush along the longer side of the board over a ruler invisible to the participant. The task consisted in following the paint brush with eyes and verbally indicating (by saying "stop") when the paint brush was positioned exactly above the index finger. The examiner recorded the number of a ruler over which the paint brush was stopped. Participants could correct their estimate if needed. The direction of the paint brush was alternated among trials.

Four estimates per each position judgement task were collected for a total of 24 estimates per subject, i.e., 4 trials × 2 position judgement tasks (Pre-MB, Post-MB) × 3 spatial shifts (10cm, 40cm, 70cm). Position estimates were calculated as the difference between the veridical and the perceived position of the index finger.

SELF-REPORT

A questionnaire was again used to assess embodiment sensations on a subjective level. Statements were here adopted from the embodiment questionnaire used by Kalckert & Ehrsson (2012). Some statements were edit and one item was constructed *ad hoc* for this study (see Appendix 3).

All the questionnaire items were read to participants and explained if needed. Participant reported their agreement/disagreement with each statement by referring to a 7-point Likert scale presented on a sheet of paper (+3: strong agreement; 0: neither agreement nor disagreement; -3: strong disagreement).
As in previous studies, responses were standardized within-subject to exclude participants' response style effect [*Ipsatisation:* $y' = (x\text{-}mean_{individual})/SD_{individual}$] (Fischer & L. Milfont, 2010). The average score of embodiment components assessed through questionnaire - *Ownership, Agency, Ownership-control, Agency-control* - were computed and submitted to statistical analyses.

5.1.2.3 Data analysis

Scores of each questionnaire component were assessed for normal distribution of residuals. Since at least one of subgroups of data failed to meet normality criteria[17] within each component dataset, differences across conditions were examined by conducing Friedman test for non-parametric within-subject design. Wilcoxon signed rank test was used for pairwise comparisons (*p*-values of comparisons were adjusted with Holm correction).
Linear mixed-effect model was conducted on proprioceptive estimates by *lmer* function; lme4 package (Bates & Sarkar, 2006). *Spatial shift* (10 cm, 40 cm, 70 cm), *Time of testing* (Pre-MB, Post-MB) and *Tested hand* (Left, right) were initially entered as fixed effects. Additionally, *Subject* and *Trial* were introduced as random factors.
Akin to proprioceptive estimates, SCR values were analyzed by conducting a linear mixed-effect model. *Spatial shift* (10 cm, 40 cm, 70 cm), was entered as fixed effects. Additionally, *Subject* and *Epoch* were introduced as random factors. The effect of *spatial shift* was examined on SCR to "no-contact" stimuli to focus on the anticipatory response to incoming stimuli.
Model selection has been carried out through automatic backward stepwise elimination of the effects introduced in the full model. According to this procedure, random parameters are tested first, then fixed effects are evaluated starting from higher-order interactions. Effects are retained when improve model goodness-of-fit - *step* function; lmerTest package (Kuznetsova et al., 2017). Lastly, a Type III mixed-design ANOVA was performed on the final model.
All data analyses were carried out with R 1.1.463 (R Core Team, 2019).

5.1.3 Results

5.1.3.1 Questionnaires responses

Ownership: ownership ratings was different across conditions, indicating a significant effect of spatial

[17] To check for normality of distribution, Q-Q plots, skewness and kurtosis were evaluated. Normality has been assumed for values of skewness and kurtosis between -1 and +1 (Doane & Seward, 2011).

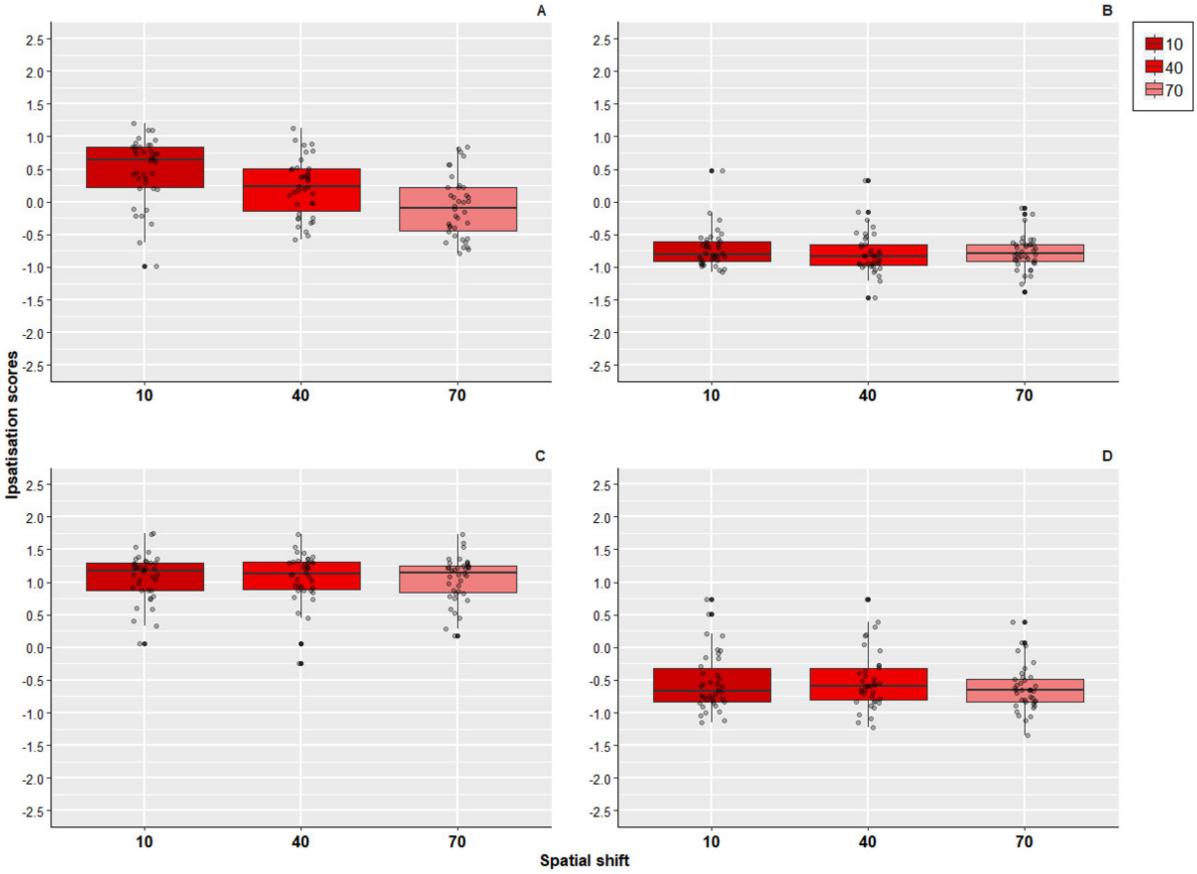


__Figure 11. Box plot of embodiment questionnaire ratings__. The median, two hinges and two whiskers of ipsatised data. Upper row: Ownership (panel A) and Ownership-control (panel B) components. Lower row: Agency (panel C) and Agency-control (panel D) components. The horizontal axis shows the three spatial shifts.

shift [χ^2 = 19.687, df = 2, p <.001]. Pairwise comparison showed significant differences between all the pairs: *10 cm* and *40 cm* [V = 495, p_{corr} = .017], *10 cm* and *70 cm* [V = 631, p_{corr} < .001] and *40 cm* and *70 cm* [V = 501, p_{corr} = .017]. Ownership-control: Ownership-controls ratings were non-significantly modulated by spatial shift [χ^2 = 0.157, df = 2, p =.925]. Agency: Agency ratings were non-significantly modulated by spatial shift [χ^2 = 1.341, df = 2, p =.512]. Agency-control: Ownership-controls ratings were non-significantly modulated by spatial shift [χ^2 = 4.409, df = 2, p =.110].

In sum, only the sense of ownership, among the all questionnaire components, significantly decreases as an effect of the increasing spatial misalignment of the mirrored hand relative to the real hand.

5.1.3.2 Position estimates

The most parsimonious model included the random effect *Subject*, the two main effects *Spatial shift* and *Time* and the second-order interaction *Spatial shift* × *Time* (Table 9). Analysis of variance run on the final model revealed a significant effect of the two-way interaction *Spatial shift* × *Time* [$F_{2,874}$ = 3.149; p = .043] and of the main factors *Spatial shift* [$F_{2,874}$ = 6.040; p <.002] and *Time* [$F_{1,874}$ = 37.155;

Fixed Structure	B	df	t-value	*p*	lower CI	upper CI
Intercept	-1.671	53.808	-4.276	<.001	-2.451	-0.891
SpatialShift40	0.322	874	1.330	.184	-0.153	0.798
SpatialShift70	-0.145	874	-0.597	.551	-0.620	0.331
TimePost	0.382	874	1.601	.109	-0.087	0.864
SpatialShift40:TimePost	0.546	874	1.593	.112	-0.127	1.219
SpatialShift70:TimePost	0.848	874	2.476	.014	0.176	1.521
Random Structure						
σ^2_{ID}	4.687					
σ^2_{Res}	4.466					
N_{ID}	38					
ICC_{ID}						

Table 8. Fitted linear mixed model and summary statistics. *The upper part lists the fixed parameters estimates (B) and their associated degree of freedom (df), t-value, 95% CI and p-value. The lower part shows random intercepts' variance (σ^2) and intraclass correlation (ICC).*

p <.001]. The analysis reveals that participants showed a larger proprioceptive drift towards the mirrored hand at the larger spatial shifts as compared to *10 cm* spatial shift (Figure 11). To quantify the extent of proprioceptive drift after the MB training, Pre-Post differences between estimated marginal means per condition were calculated. Positive values denote a shift towards the extra-personal space and negative values denote a shift towards body midline. Proprioceptive drifts per condition: *10 cm* = +.39 cm, *40 cm* = +0.93 cm and *70 cm* = +1.24 cm.

5.1.3.3 Skin Conductance Response

The most parsimonious model included both random effects *Subject* and *Epoch*. Conversely, the fixed factor *Spatial shift* did not increase model goodness-of-fit. Given the analysis exclude any effect of the factor under investigation, SCR has not been further examined.

5.1.4 Discussion

This study aimed to explore spatial constraints of the MB illusion by means of physiological, proprioceptive and subjective illusion-related outcomes. To this end, the spatial location of the seen hand was systematically manipulated across three different condition of MB training. Generally, results show that the increasing spatial misalignment between the alien hand and the real hand modulates the verbal reports and proprioceptive outcomes, but it does have any noticeable effect on SCR to approaching noxious stimuli.

Ownership ratings was significantly higher when the mirrored hand was seen almost overlaying participant's hand. However, by increasing the spatial mismatch between the seen and the felt hand the strength of illusion declined accordingly. This results are in agreement with Preston (2013) and indicate that the subjective strength of the illusion modulates within the peri-personal space because they become weaker as the visual feedback moves away from peri-hand space and from the body midline. The inhibition of the ownership illusion for body placed at the limits of peri-personal space has been

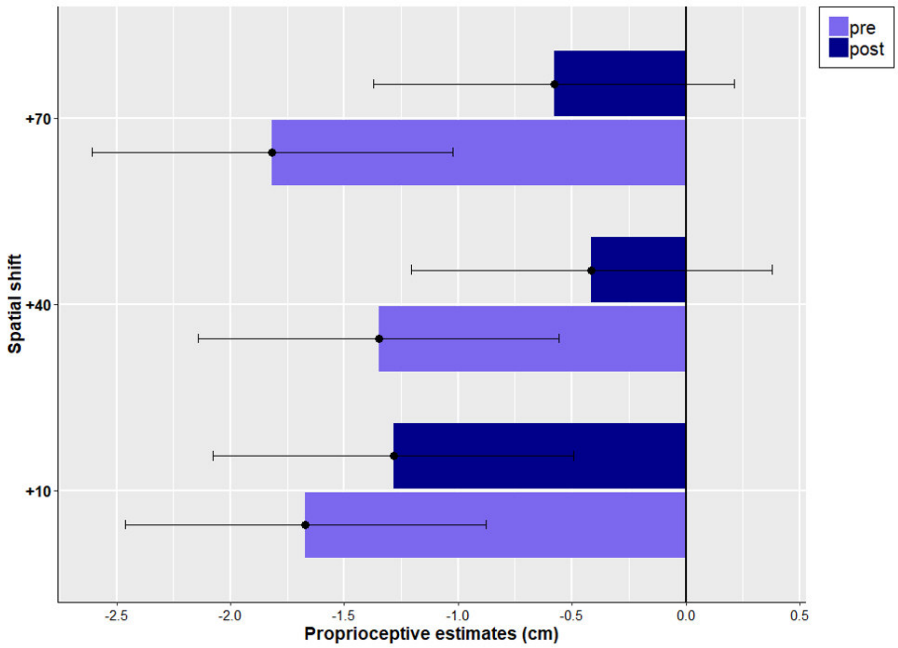


Figure 12. Proprioceptive judgments. *Estimated marginal means (± 95% CI) of perceptual estimates before and after the MB training. Estimates are represented as the amount of shift away from the position of the real hand (x = 0). Positive values denote a shift towards the mirrored hand and negative values denote a shift towards the body midline.*

demonstrated also by virtual reality studies (for a review: Kilteni et al., 2015). As predictable, the illusorily agency over the alien hand does not decrease. In fact, sense of agency can apply to close as well as distant feedbacks as long as the temporal mapping between intention and consequences is preserved (Kalckert & Ehrsson, 2014b). Conversely, it is more likely to modulate as an effect of multisensory synchrony and type of movement (see Experiment 1.1 and Experiment 2).

The proprioceptive drift is used as a proxy of the proprioceptive encoding of the hand position. Generally, participants tended to misperceive the position of the hand towards the trunk regardless of the illusion (see proprioceptive drifts at baseline, Figure 11). Speculatively, such a general perceptual bias might account for the small magnitudes of drift in comparison to previous studies (Preston, 2013; Zopf et al., 2010). Unlike classical RHI setup, the mirrored hand was seen lateral to the real hand. This arrangement might have contrasted the proprioceptive drift towards the hand related to the illusion of embodiment.

The two-way interaction *Spatial shift* by *Time of testing* highlights that the extent of drift gradually increases in accordance with the amplitude of the spatial discrepancy between the real and the mirrored hand. This modulation of the proprioceptive drift disproves the initial hypothesis, since it appears to be increasingly biased towards the location of the hand in the mirror. This indicates that the proprioceptive drift does not decrease when the mirrored hand approaches the extra-personal space. This trend of result is in disagreement with Kalckert & Ehrsson (2014b), who concluded that proprioceptive drift following the active RHI shows up at 12 cm, but not at 27.5 cm. In that study, however, the occurrence of drift towards the rubber hand was based on the comparison between synchronous and asynchronous

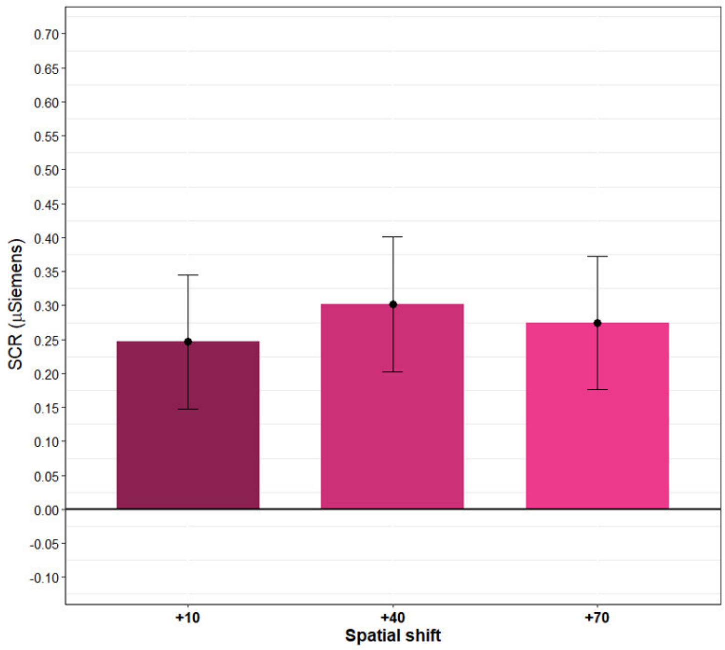


Figure 13. Skin Conductance Response. *Estimated marginal means (± 95% CI) of peak-to-peak skin conductance response to no-contact stimuli.*

conditions of stimulation. Akin to current results, a small perceptual shift towards the model hand (about .5 cm) occurred at both distances under synchronous stimulation. Notwithstanding, such a comparison may be questionable because RHI modulation by distance was there explored relative to the vertical plane. Previous references about the modulation of the proprioceptive drift on the horizontal plane in the classical RHI (Preston, 2013; Zopf et al., 2010) suggests that in any case the fake hand is positioned lateral to the real hand and further to the body, a small non-significant perceptual shift away from the fake hand towards the body can be observed with respect to the conditions in which the fake hand is positioned medially (as in the classical RHI) (Preston, 2013). As such, proprioceptive drift during visuo-tactile illusion on the horizontal plane modulates in the opposite direction with respect to present proprioceptive data.

Conversely, current data are in line with previous accounts suggesting a gradual recalibration of hand position towards the visually specified position (the mirrored hand) and away from the proprioceptively specified location (the real hand) during the MB illusion, i.e., the *visual capture effect* (Holmes, Crozier, & Spence, 2004; Holmes & Spence, 2005; Medina et al., 2015). The visual capture effect was also observed to be of larger magnitude when the participant was asked to move the hand during illusion induction compared to when he was to rest his hand in front of the mirror in a static position (Holmes & Spence, 2005; Medina et al., 2015). Current results expand these previous results suggesting that the recalibration persists for the mirrored hand at further locations away from the body midline.

Speculatively, they might indicate that hand position remapping on the horizontal plane during RHI-like illusions is computed differently based on multisensory inputs at stake, i.e., visuo-tactile *vs.* visuo-motor. Given such a difference was not systematically addressed and it is only conjecturally hypothesized, whether the interplay between different types of cross-modal integration and peri-personal space has a different effect on hand location estimates in MB illusion may be investigated in future.

As for the physiological measure of the MB illusion employed here, the effect of distance did not represent an explanatory variable for the data of autonomic responses to expected noxious stimuli. Interesting evidence of a relationship between sense of ownership and SCR derives from studies on brain-damaged patients. Romano et al. (2014) found that the sense of disembodiment of a body-part in somatoparaphrenia is accompanied by a significant reduction in the physiological response to noxious stimuli directed towards the affected limb. The authors speculate that this finding is suggestive of a disruption in body representation extending to peri-personal space relating to protective behaviour. Additionally, Garbarini et al. (2014) observed that patients with a pathological embodiment of extracorporeal hand demonstrated a greater SCR amplitudes in response to stimuli delivered to an alien hand (pathologically embodied) placed in the affected side compared to stimuli delivered to the their own contra-lesional hand. Accordingly, this provide evidence to the idea that sense of ownership produces top-down modulation of SCR to noxious stimuli threatening one's own body part.

In the present study, the lack of consistency between physiological and subjective indices of the illusion of ownership might indicate that the mere modulation of spatial discrepancy between the real and the fake hand is not by itself enough to disrupt sense of ownership at an implicit level. Hence, the illusion of ownership can persist so long as any postural violation is introduced (e.g., different orientation of the mirrored limb). As such, the inhibition of subjective reports of the illusion may be also ascribed to the effect of semantic and higher-order cognitive processes such as the structural knowledge of the human body (Longo, Azañón, & Haggard, 2010).

To conclude, this study provides evidence for a different modulation of proprioceptive, subjective and physiological correlates of the MB illusion. The sole modulation of the subjective ownership is in keeping with a role of personal space on the intensity of the illusion. Nonetheless, whether it results from perceptual more than cognitive constraints can hardly be disentangled based on available results. Finally, proprioceptive data confirm previous evidence suggesting a nonlinear relationship between sense of ownership and this objective measure of multisensory integration (Rohde, Luca, & Ernst, 2011). Hence, a different experimental manipulation may be better capable to address malleability of body representation in schizophrenia.

6 General discussion and conclusion

Schizophrenia has long been conceived as a severe disorder of Self. Several symptoms (e.g., verbal hallucinations or thought insertion) can be conceptualized as a loss of cohesion within the various facets of the Self. A crucial aspect of the Self is its inherent link with the body. From a phenomenological perspective, the notion of *ipseity* (i.e., the most non-conceptual and somatic form of self-knowledge, which represents the inner nucleus of the Self) aims to capture such a link. On the other hand, neuroscientific research extensively demonstrated that self-experience is strongly related to the effective integration of bodily signals (Blanke, 2012).

Searching for novel clues of self-body recognition in schizophrenia, we carried out a series of three studies focused on the contribution of sensorimotor integration mechanisms to the perception of one's own body in schizophrenia. We started from the observation that previous accounts in the field were limited to the investigation of body representation by means of the RHI. Generally, these studies revealed a more susceptibility to the experimental procedure compared to healthy people as the illusion of ownership is rated more intense, arises faster and it emerges even under asynchronous visuo-tactile stimulation. Nonetheless, the RHI elicits ownership sensations for a fake hand by visuo-tactile stimulation, leaving the agency subcomponent of embodiment relatively untouched. As suggested by Gallagher and Trigg, sense of ownership and sense of agency form an interdependent pairing in bodily perception and they should not be addressed in isolation for the investigation of self-disturbances in schizophrenia (Gallagher & Trigg, 2016). In view of sense of agency disturbances experimentally highlighted by several studies on self-recognition of movements, we addressed body perception in schizophrenia by means of a visuo-motor BOI, i.e., the MB illusion. The MB illusion, by relying on sensorimotor integration processes, allows the explicit elicitation of both determinants of body awareness. Based on previous studies showing sensorimotor deficits in schizophrenia, we predicted an abnormal modulation of the subjective and objective correlates of the illusion.

In the first study (**Experiment 1**), we explored the modulation of the illusion of the embodiment of a moving alien hand by using the mirror box apparatus. The experience of incorporation, which entails illusorily sensations of ownership and agency upon the alien hand, was assessed through a dedicated questionnaire. Participants were also asked to accomplish the forearm bisection task, an implicit measure of embodiment. Differently from healthy participants, subjective sense of agency and bisection estimates did not modulate across conditions in the schizophrenia group. We concluded that impaired sensorimotor processes may explain the altered modulation of these indices of the illusion in patients. Since that, we put forward that two non-mutually exclusive sensorimotor deficits might underlie these findings, i.e., an enlarged TBW for visual and proprioceptive feedback and/or dysfunctional motor prediction mechanisms.

In two further follow-up studies, we sought to explore the reasons for the observed distal shift of the perceived forearm midpoint. **Experiment 1.1** examined the possible relationship between the distal midpoint shift and the arising of sense of agency. **Experiment 1.2** investigated the association between the distal midpoint shift with the allocation of spatial attention towards the hand. Both studies disproved the hypotheses under investigation. Hence, other reasons than those explored may underlying this perceptual effect.

In the light of the two potential interpretations of results in Experiment 1, we carried out a second study (**Experiment 2**) aimed at clarifying which of the two hypothesized deficits could better explain the altered pattern of modulation of the MB illusion in patients. To this end, the joint impact of (a) the visuomotor time-lag – the temporal shift between participant's hand and the mirrored hand movements - and (b) the mode of movement – whether participant performed active or passive movements - on the illusion of embodiment was investigated. The first experimental manipulation served to examine the role of the TBW extent on multisensory integration processes. The second manipulation aimed at verifying whether the occurrence/absence of motor predictions affects visuo-proprioceptive integration underlying the illusion. Preliminary results from this study show an altered modulation of illusorily body ownership in schizophrenia, which seems to be mostly accounted for by an enlarged visuo-proprioceptive TBW. This result might indicate that an abnormal integration of afferent signals (and/or altered sensory expectations) is strongly implicated in the disruption of self-body ownership (intended as the self-identification with a body) in schizophrenia. This conclusion, however, warrants caution given the small size of the patients group.

At the last, we designed an additional study (**Experiment 3**) to addressed in the future the hypothesis that body representation is abnormally malleable in schizophrenia. According to this hypothesis, higher ratings of ownership illusion have been regarded as the effect of a weak internal model of the body. One might speculate that if patients' body representation is so extremely plastic, they could be expected to easily embody extra-corporeal hand positioned at an implausible distance from the body. To test whether spatial discrepancy inhibits sense of ownership during the MB illusion, an exploratory experiment has been carried out in healthy people beforehand. Results from this experiment are only partially in agreement with the hypothesis of spatial constraints (i.e., peri-personal space) of the MB illusion. Indeed, the expected decrease of the illusion was observed at a subjective level, but not at the objective level. Therefore, a different manipulation might better address the relationship between body ownership and spatial body plausibility in healthy and clinical population.

Despite incomplete and provisional, this experimental enquiry indicates that impaired visuo-motor integration processes in schizophrenia do not merely impact on sense of agency, but also on the processing of the own body, as suggested by the abnormal modulation of the objective index of embodiment (Experiment 1) and by the altered modulation of sense of ownership (Experiment 2). These findings expand those based on the RHI providing empirical evidence of the fact that disturbances of body representation and body awareness in schizophrenia can be dependent on defective sensorimotor integration processes for action.

It is apparent that BOIs like the MB illusion cannot fully capture the heterogeneity of self-disorders in schizophrenia. However, they may represent a fruitful field of future investigation in psychiatry (Noel et al., 2018) because, by assessing self-body identification, they tap into underpinnings of self-identification. For instance, they might represent a viable way to explore psychopathological self-experiences that might be supposedly rooted in altered visuo-proprioceptive integration, e.g., catatonia or motor passivity.

A recent suggestion is that bodily illusions stem from neural processes for self-recognition, these latter being framed within the free-energy account of the cortical function (Apps & Tsakiris, 2014). According to the free-energy principle, the brain is in the continuous attempt to minimize the amount of free-energy (i.e., surprise) in the sensory inflow caused by a constantly changing environment. To fulfil this need, the brain iteratively predicts the sensorial outcomes generated by each environmental event (*predictive coding*).[18] Whenever a prediction cannot explain away sensory evidence because unpredictable, a *prediction error* (i.e., phasic amount of surprise) results. Under these circumstances, the brain dynamically updates top-down predictions so to maintain low level of entropy (*perceptual inference*)[19]. Two main facts underpin the way free-energy minimization is achieved. First, predictions originate from internal representational models (or beliefs) encoding the more likely cause for a sensory scenario, i.e., *generative models*. Second, the dynamic update of generative models and predictions follows Bayesian rules. Thus, a generative model is associated to a probability distribution reflecting the degree of belief in the validity of the model. Given this, the process of update is formalized in the *prior belief* (the probability of an event based on previous experience), the *likelihood* (the probability of the event based on the actual sensory evidence) and the *posterior belief* (the updated probability of the event based on the combination of prior with likelihood) (Adams, Stephan, Brown, Frith, & Friston, 2013). Relevant to the issue under investigation, the minimization of free-energy occurs through the hierarchical organization of the brain, with higher-level areas generating predictions towards lower areas any time they are engaged by a sensory event. Multisensory body areas, at the top of the hierarchy, encode the prior probability of multisensory events for whom the most parsimonious

[18] In this setting, the corollary discharge is like any other prediction which specifically contains proprioceptive and kinaesthetic expectations about the movement (Apps & Tsakiris, 2014).
[19] Alternatively, the brain acts upon the environment to modify the sensory inflow and to make it predictable (*active inference*).

explanation has been the existence of a bodily Self, e.g., the detection of visuo-proprioceptive congruencies in front of a mirror can only be explained away by a common "cause" for the perception of those synchronous inputs, that is the Self. In the free-energy framework, this implicates that there is no Self without multisensory conception of it, but also that the representation of the bodily Self is probabilistic. As such, the bodily illusion arises when the sensory surprise caused by an extracorporeal limb is explained away at a multimodal node of the hierarchy for which there is usually minimal surprise. This can be possible because of the multimodal abstract predictions of one's own body are transiently updated during e.g. the RHI, leading to an increase in the distributional probability of the visual feedback from the extra-personal object as part of the body (Apps & Tsakiris, 2014; Tsakiris, 2017).

The free-energy perspective explains psychotic symptoms as a failure of *empirical priors*. These latter encode the distributional probability of the parameters of the priors (i.e., mean and variance). They can be referred to as "beliefs about beliefs" and they reflect the expected precision of a generative model. According to this view, psychotic symptoms are the behavioural manifestation of a reduction of high-level prior precision because of aberrant empirical priors (Adams et al., 2013; Sterzer et al., 2018). For instance, a reduction in prior precision of internal model of the body within multisensory areas might account for the abnormal malleability of body representation hypothesised by RHI studies in schizophrenia.

It is worth noting that according to free-energy model self-recognition is a highly distributed process involving neural multisensory areas of the brain. Conversely, other experimental perspectives stress the role of specific neural networks in the arising of a cohesive sense of Self. According to Northoff's model, a proper sense of Self originates from a balanced communication between the Default Mode Network (DMN) and Central Executive Network (CEN). The DMN, involving the medial prefrontal cortex, the posterior cingulate cortex and the precuneus, is usually activated during internally-directed activities, such as internal mental contents, self-oriented thoughts as well as interoceptive and proprioceptive perceptions from the inner body. The CEN, including the lateral prefrontal cortex bilaterally and the parietal cortex, is instead recruited during externally-directed activities, goal-oriented cognitive tasks or the processing of exogenous stimuli (Northoff & Duncan, 2016). In this framework, the DMN would be involved in body perception and self-ascription of bodily input. A fundamental disruption of the spatio-temporal structure of the brain activity would be responsible for decoupling between CEN and DMN in schizophrenia. This would entail the impossibility to appropriately segregate internally- from externally- contents and the consequent development of Ego-disturbances, like agency disruption (Northoff & Duncan, 2016; Robinson et al., 2016). Additionally, the reduced connectivity between the anterior insula and the DMN would account for the incapability to self-ascribe somatic information and for the experiences that those somatic sensations come from the environment. The body becomes disowned, with a reduce possibility to experience sense of ownership and sense of agency (Northoff & Stanghellini, 2016; Robinson et al., 2016).

To conclude, we hypothesise that the abnormal modulation of MB illusion indices observed in previously reported studies may be the outcome of a disbalance between interoceptive and exteroceptive sensory information, either in terms of afference or in its predictive counterpart or both. As recently suggested, psychotic experiences may be regarded as cases of *perceptual incoherence*. Perceptual incoherence (i.e., incoherence across sensory streams of information) origins either from conflicting cross-modal inputs (eg. asynchronous stimuli) or from a disbalance weighting across multisensory inputs (e.g., local anaesthesia). In this view, a reduction of somatosensory signals processing (which is strictly related to self-perception) underlies several disturbances of the perceived sensory Self, such as depersonalization, blurred boundaries or abnormal agency and ownership (Postmes et al., 2014).

In agreement with this assertion, the abnormal modulation of the MB illusion might reveal a scarce reliability of proprioception (proprioceptive feedback and/or proprioceptive prediction). The deficit would introduce a derangement within sensorimotor integration processes that would be able to account for the abnormal modulation of self-body subjective perception (i.e., subjective sense of ownership and sense of agency) and for the abnormal modulation of bisection performance. In fact, during the forearm bisection task participants can only rely on proprioception to carry out the task. Estimates provided by participants with schizophrenia show in fact enhanced variability that might be the result of an extremely noisy and/or inconstant somatic information. The subjective counterpart of this phenomenon would be an abnormal overreliance on visual information from the mirror. Hence, sense of ownership judgment would be high until larger visuo-proprioceptive discrepancies, and the perceived distinction between an active and a passive movement would be reduced.

Proprioception, as other interoceptive signals, constitutes an information that unambiguously belongs to us: It provides information that can only originate from within (i.e., from one's own body) and are not available for the perception of external objects and bodies (De Vignemont, 2011). Therefore, the unreliability of proprioceptive signals might play a crucial role in self-body perception and self-body recognition.

The present experimental work has at least a couple of limitations to mention. First, Experiment 2 lacks a perceptual measure for body agency and/or body ownership. In that study, the solely subjective data collected by participants may be subjected to bias hard to control. Especially for patients, this may turn out in self-reports that may not only be relative to the extent of visuo-proprioceptive synchrony or movement modality detected, but also to subjects' susceptibility or to a general tendency to give higher responses or to a perseverative bias (Shaqiri et al., 2018). Ipsatisation of scores served to limit as much as possible these possibilities and to focus on modulation across conditions. Additionally, we distinguished between experimental items and control items to avoid averaging between them. Second, we did not sample according to psychopathological symptom profile (e.g., Graham-Schmidt et al., 2016, 2018; Graham et al., 2014) because we set out with the purpose of a broad assessment of body representation in schizophrenia. Nonetheless, certain cluster of symptoms, like passivity symptoms, may play a role in body illusion which purportedly capitalize on the same neural processes for sense of agency and its disruption. Third, our clinical groups are made up of patients in both acute and stable phase. However, taking into consideration the stage of psychosis and/or the course of symptoms in longitudinal designs may provide a more fine-grained outline of body ownership and agency disturbances related to schizophrenia and psychoses in general.

Appendix 1

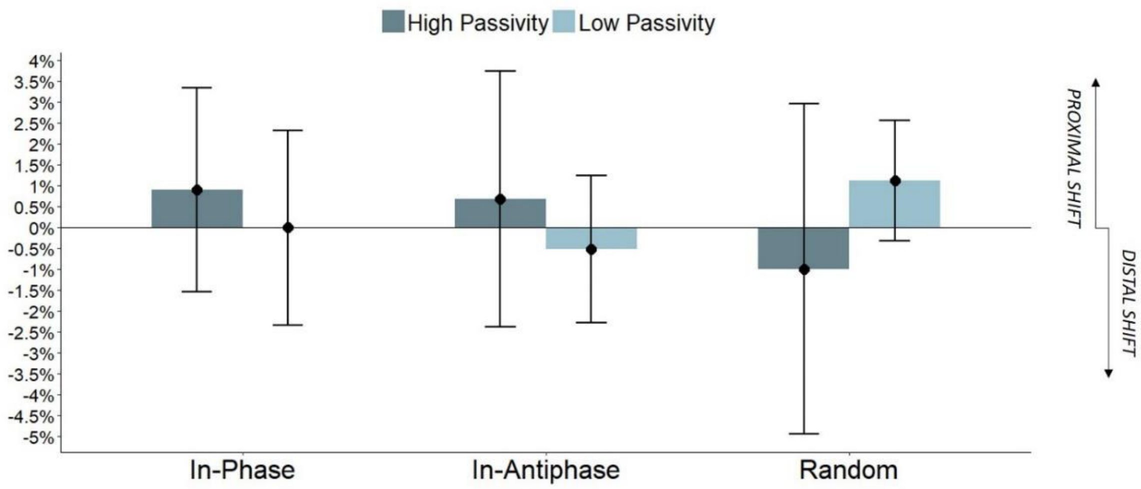
Embodiment Questionnaire Experiment 1 - Questionnaire statements
(adapted from Longo et al., 2008)

1. *Mi sembrava di guardare direttamente alla mia mano oltre lo specchio.*
2. *Sembrava che la mano nello specchio cominciasse ad assomigliare alla mia mano.*
3. *Sembrava che la mano nello specchio mi appartenesse.*
4. *Sembrava che la mano nello specchio fosse la mia mano.*
5. *Sembrava che la mano nello specchio fosse una parte del mio corpo.*
6. *Sembrava che la mia mano fosse nel posto dove era la mano nello specchio.*
7. *Sembrava che la mano nello specchio fosse nel posto dov'era la mia mano.*
8. *Sembrava che avrei sentito un tocco sulla mano nello specchio.*
9. *Sembrava che avrei potuto muovere la mano nello specchio se avessi voluto.*
10. *Sembrava che fossi io a controllare la mano nello specchio.*
11. *Sembrava che la mia mano diventasse di gomma.*
12. *Sembrava che non fossi capace di muovere la mia mano.*
13. *Sembrava che avrei potuto muovere la mia mano se avessi voluto.*
14. *Sembrava che non potessi dire dove si trovasse realmente la mia mano.*
15. *Sembrava che la mia mano fosse sparita.*
16. *Sembrava che la mia mano fosse fuori dal mio controllo.*
17. *Sembrava che la mia mano si muovesse verso quella nello specchio.*
18. *Sembrava che la mano nello specchio si muovesse verso la mia mano.*
19. *Sembrava che avessi tre mani.*
20. *Ho trovato quest'esperienza piacevole.*
21. *Ho trovato quest'esperienza interessante.*
22. *Muovere il mio dito era piacevole.*
23. *Ho avuto la sensazione di dolore e punture sulla mia mano.*
24. *Ho avuto la sensazione che la mia mano fosse intorpidita.*
25. *Sembrava come se l'esperienza della mia mano fosse meno vivida del normale.*
26. *Ho trovato che mi piacesse la mano nello specchio.*
27. *Sembrava come se potessi sentire un tocco nel posto dove la mano nello specchio sarebbe stata toccata.*

Post-hoc analysis on bisection data

To explore possible associations between the trend of bisection data and the passivity profile, the patient group was split in two subgroups according to the severity of passivity symptoms. To this end, we took into consideration the following cluster of symptoms: (a) Delusions of being controlled, (b) Delusions of mind reading, (c) Thought broadcasting, (d) Thought insertion, (e) Thought withdrawal. Scores were averaged within each subject. Patients with an average score < 1.5 were grouped in the low passivity profile subgroup (14 patients), while patients with an average score > 2.5 were clustered in the high passivity profile subgroup (9 patients).

Bisection data were then modeled as depending on all experimental predictors (fixed covariates: *Group*, *Congruency* and *Time*) after adjusting for random effects *Trial* and *Subject.* Analysis of variance run on the final model revealed significant differences for the two-way interaction *Group* × *Congruency* [$F_{2,1348} = 4.915$; $p = .007$] and the three-way interaction *Group* × *Congruency* × *Time* [$F_{2,1348} = 6.177$; $p = .002$]. Results are not easily interpretable. The small size of subgroups may have prevented a clearer pattern to emerge.



Midpoint shift after MB training in the two schizophrenic subgroups.

Appendix 2

Embodiment Questionnaire Experiment 2 - Questionnaire statements
(adapted from Kalckert & Ehrsson, 2012)

1. *Mi sembrava di guardare direttamente la mia mano oltre lo specchio.*
2. *Mi sembrava che la mano vista nello specchio fosse una parte del mio corpo.*
3. *Mi sembrava che il dito della mano nello specchio e il mio dito reale si muovessero nello stesso posto.*
4. *Mi sembrava che la mano osservata nello specchio mi appartenesse.*
5. *Sembrava che la mia mano reale diventasse di gomma.*
6. *Sembrava che avessi più di una mano destra/sinistra.*
7. *Sembrava che la mano vista nello specchio si muovesse verso la mia mano.*
8. *Sembrava che la mia mano reale fosse sparita.*
9. *La mano osservata nello specchio si muoveva proprio come volevo, come se stesse obbedendo alla mia volontà.*
10. *Sembrava che fossi io a controllare i movimenti della mano vista nello specchio.*
11. *Sembrava che fossi io a causare i movimenti della mano osservata nello specchio.*
12. *Ogni volta che il mio dito iniziava a muoversi, mi aspettavo di vedere il dito della mano nello specchio muoversi contemporaneamente.*
13. *Mi sembrava che la mano osservata nello specchio stesse controllando la mia volontà.*
14. *Sembrava che la mano vista nello specchio stesse controllando i miei movimenti.*
15. *Mi sembrava di sentire i miei movimenti nello spazio compreso tra la mia mano reale e la mano nello specchio.*

Appendix 3

Embodiment Questionnaire Experiment 3 - Questionnaire statements
(adapted from Kalckert & Ehrsson, 2012)

1. *Mi sembrava che la mano nello specchio cominciasse ad assomigliare alla mia mano.*
2. *Sembrava che la mia mano reale e il riflesso della mano che vedevo si trovassero alla stessa distanza dallo specchio.*
3. *Sembrava che il riflesso della mano nello specchio si sovrapponesse alla (posizione della) mia mano reale.*
4. *Mi sembrava che la mano nello specchio mi appartenesse.*
5. *Sembrava che la mia mano reale diventasse di gomma.*
6. *Sembrava che avessi più di una mano destra/sinistra.*
7. *Sembrava che la mano nello specchio si muovesse verso la mia mano.*
8. *Sembrava che la mia mano reale fosse sparita.*
9. *La mano nello specchio si muoveva proprio come volevo, come se stesse obbedendo alla mia volontà.*
10. *Sembrava che fossi io a controllare i movimenti della mano nello specchio.*
11. *Sembrava che fossi io a causare i movimenti della mano nello specchio.*
12. *Quando il mio dito iniziava a muoversi, mi aspettavo di vedere il dito nello specchio iniziare a muoversi contemporaneamente.*
13. *Mi sembrava che la mano nello specchio stesse controllando la mia volontà.*
14. *Sembrava che la mano nello specchio stesse controllando i miei movimenti.*
15. *Mi sembrava di sentire i miei movimenti nello spazio compreso tra la mia mano reale ed il riflesso della mano nello specchio.*
16. *Sembrava che la mano nello specchio avesse una sua propria volontà.*

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