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How embodiment shapes our perception: evidence of body and space

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ABSTRACT

A large variety of sensory input from either the world outside the body or the body itself, are continuously integrated in the brain in order to create supra-modal and coherent mental representations of our own body. Such representations provide clues that are useful movement, stimulus localization, awareness of the bodily self, according to different theoretical models.

Plasticity is a fundamental characteristic of the nervous systems, allowing constant adaptive changes in mental functions and behaviour. Thanks to this, even body representations can change according to experience and, crucially, they can be temporarily altered by means of experimental protocols.

In the present work, we were interested in assessing the plasticity of the subjective metric of the body, and the effect of temporary changes in the body metrics on the processing of corporeal and spatial information. To this aim, two types of bodily illusion were used, i.e. the Mirror Box Illusion and the Full-Body Illusion, due to their known effects inducing strong modulations of body representation. The core mechanism accounting for the efficacy of these experimental procedures is likely to be the process of embodiment of an alien body part (i.e. the hand reflected in the mirror, in the mirror box illusion or the avatar in the full body illusion)

In experiment 1 we used a visuotactile Full-Body Illusion-like paradigm (FBI) induced with a new, portable, technological setup, to assess the feasibility and the replicability of the BI for bodies of different sizes. Using this paradigm, we confirmed that it is possible to induce and replicate in the same participant, the embodiment towards mannequins of standard or bigger sizes. In experiment 2 and 3 we investigated body metric representation of the leg, and whether it can be plastically modulated by embodying mannequins of different sizes. To address this issue, we measured the effect of FBI induced by different body sizes, over a Body Distance Task (BDT), i.e. the assessment of the perceived distance between two touches applied to the participant's leg. We found that the FBI affects the subjective experience of embodiment and that this subjective sensation is also accompanied by a change in the perception of body metric that goes hand-in-hand with the current size of the embodied legs.

Since we confirmed that, in healthy subjects, the metric representation of the body can be modulated by embodying bodies holding different sizes, we addressed a similar question in patients with hemiplegia. In experiment 4, using a body bisection task we first observed that hemiparetic post-stroke patients show a proximal bias in the metric representation of their affected upper limb, likely due to non-use. Critically, we found that this bias shifts distally, towards the objective midpoint after a Mirror Box (MB) training session, compared to a control training without the mirror. In a further experiment In Experiment 5 we found a similar modulation of subjective body metric in a group of

patients suffering from Ideomotor Apraxia, treated with a modified version of the MB setup, which was accompanied by an improvement in the programming of motor plans.

In the last two studies (experiments 6 and 7) we focused more on the relationship between body metric and space representations. First, we tested the hypothesis that an altered body representation could modify the way in which individuals estimate the distance to spatial targets in a Motor Imagery Task. Our results showed that participants imagined walking faster after having been exposed to an illusion of embodiment of longer. Furthermore, we found that the illusory embodiment of longer legs can affect the estimation of allocentric distances in extra-personal space. On the one hand, the embodiment of longer legs reduced the perceived distance in meters, on the other hand, the embodiment of the same legs produces an enhancement of the number of steps that participants imagined they would have needed to walk between the same landmarks. These results emerged considering the baseline abilities of each participant to estimate allocentric distances in far space both in meters and in steps.

In conclusion, we confirmed that it is possible to induce provisional modifications of the metric representation of the body, by means of body illusions. We showed that body representation is malleable to the point to shape our perception of body metric and our ability to estimate distances in the external world both in terms of reachability and allocentric distance estimation.

Such plasticity of body representation and body-space interaction, obtained with rather simple manipulations inducing the embodiment of bodily visual signals, gives important clues for the understanding of body representation and for the rehabilitation of its disruption in neurological patients.

1. INTRODUCTION

1.1. BODY PERCEPTION AND REPRESENTATION

The body holds an accurate description in the brain relative to the anatomical structure of the body and the spatial relations between body parts, as well as about ongoing information of the actual position of each body part (Berlucchi & Aglioti, 2010; Maravita, et al., 2003; Sposito, et al., 2012; Vallar, & Maravita, 2009). We continuously receive many different inputs from either the world outside the body or the body itself, that the brain integrates in order to create supra-modal and coherent mental representations of our own body (Berti, 2013). Alternative cognitive models have split body representation into different components trying to outline their functions (Carruthers, 2008; F. De Vignemont, 2010; Longo et al., 2010; Schwoebel & Coslett, 2005).

In 1980, Paillard strongly influenced by the Perception-Action model of vision, suggested distinguishing the identified body and the situated body (Paillard, 1980). This subdivision was the very first attempt to define the dyadic model of body representation. The dyadic taxonomy (Dijkerman & de Haan, 2007, Paillard 1999) distinguish between the body schema, a sensorimotor representation of the body that guides actions (e.g. information about the body necessary to move such as posture, limb size, and strength) and the body image that groups all the other representations about the body that are not used for action, whether they are perceptual, conceptual or emotional and allows perceptual identification and recognition (e.g., body part recognition) (de Vignemont, 2010). Paillard et al. (1983) reported a patient with a left posterior cortical lesion who could point to tactile targets on her right hand that she was unable to detect on a pictorial representation of the body; this condition was defined “numbsense”. In 1999 the authors suggested that “numbsense” patients have a specific deficit in the perceptual representation of body target (body image), while the sensorimotor representation (body schema) remains unaffected. He described the opposite dissociation in a patient who suffered from peripheral deafferentation, but with an intact motor system. She was able to verbally identify the location of tactile stimuli, but she could not point towards the same stimuli. This would be consistent with an impairment in body schema, with preserved body image (Dijkerman & de Haan, 2007).

On the other hand, Schwoebel & Coslett (2005) studying body representation disorders in a group of 70 stroke patients, observed a triple dissociation between body representations components, suggesting a triadic model. The authors proposed a similar concept of body schema as a dynamic representation of the relative positions of body parts derived from multiple sensory and motor inputs (e.g. proprioceptive, vestibular, tactile, visual, efference copy) that interacts with motor systems in the generation of actions (Schwoebel, Boronat, & Branch Coslett, 2002). They described the body image as a lexical-semantic representation of the body, including body part names, functions, and relations with objects (Coslett, Saffran, & Schwoebel, 2002). Finally, they complemented the model with the concept of body structural description: a topological map of locations derived from visual input that defines body boundaries and proximity relationships (Buxbaum & Coslett, 2001; Sirigu, Grafman, Bressler, & Sunderland, 1991). Schwoebel & Coslett (2005) asked participants to undertake three different tasks, each one specific for one component of the triadic model. Tasks designed to assess the body schema included the hand imagery/action task and the hand laterality task. In the first one, subjects were asked to imagine making or execute a specified movement 5 times. In the second one, subjects were shown a picture of a hand and asked to indicate if the stimulus is the right or left hand. Tasks designed to assess the body structural description required subjects to localize isolated body parts or tactile input, and match body parts by location. Tasks assessing the body image required subjects to match body parts by function, and to clothing or objects. The analysis of the performances suggested that the body schema, body structural description, and body image are dissociable representations referred to different brain damages.

The body schema seems to play a crucial role in body representation and is a component mentioned by most authors. This representation is defined as a dynamic sensorimotor representation that guides perception and actions, and it is supposed to be mostly out of awareness contributing to body-space interactions mostly in an automatic fashion (De Vignemont, 2010; Dohle et al., 2004; Haggard & Wolpert, 2005; Longo et al., 2010). The other body representations are not used primarily for action and have been described as to occur at a more conscious level. However, there is no agreement about that, and the debate about the taxonomy of those representations is still open (De Vignemont, 2010; Longo et al., 2010).

From our viewpoint it is interesting the proposal made by Longo et al. (2010) who describes body representation to be composed by the *somatorepresentation*, the cognitive reference model of the body, and the *somatoperception* which would be the perceptive representation of the body as the source of first-person experiences (Longo, Azañón, & Haggard, 2010). In particular, the authors suggested that somatoperception receives information from three sources. The postural schema is an online representation of the body updated with movements, it was introduced by Head and Holmes (1911) as a continuously updated representation of the posture of the body, and it has been then addressed at as body schema. Proprioceptive afferent information, together with efferent signals from the motor system describe the online configuration of the body. The body model, a description of the body size and shape, seems to contribute to localisation of the body in external space and perception of the size and shape of tactile objects. Finally, the superficial schema, that is based on the somatosensory representation of the body in the brain, mediates the localisation of somatic sensations on the body surface. To properly understand how these three sources of information work together, we can take into consideration the process of tactile remapping. Tactile remapping is the computation of the external spatial location of an object touching the skin and requires the use of all three body representations. The superficial schema allows locating the touch on the body surface, considering the configuration of the joints. In order to establish the external spatial location of the touched body part, the brain needs to combine information about joint configurations (implicating the postural schema) with representations of the length of body segments connecting joints, involving the body model of its metric properties (Longo et al., 2010).

A more recent review of the previous model by Tamè, Azañón and Longo (2019) advocates for an additional source of information for somatoperception. Focusing on the process of tactile remapping, the authors considered to be necessary not only the integration of touch and online proprioceptive signals but also the offline representation of the most plausible spatial locations for a given touch (Azañón and Soto-Faraco, 2008; Overvliet et al., 2011) or the most likely configurations of the body in space (Yamamoto & Kitazawa, 2001; Romano et al., 2017). Figure 1 shows the complete model of somatosensory processing.

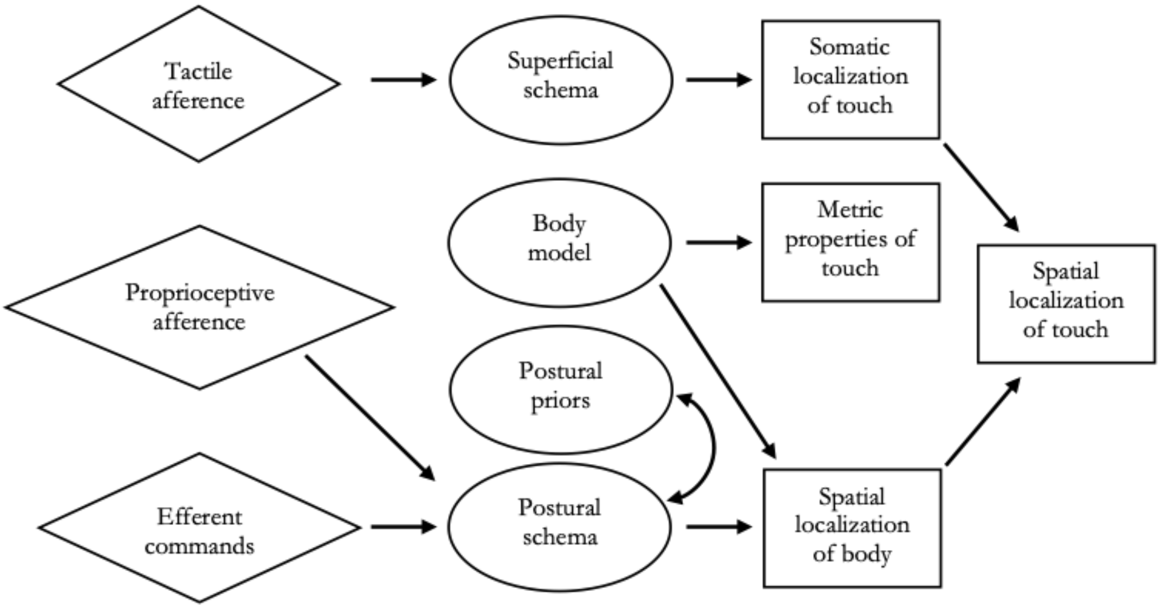

Figure 1. **Representation of the revised model of somatosensory processing** by Tamè, Azañón, and Longo (2019), formerly defined by Longo, Azañón, and Haggard (2010).

1.1.1. *Body metric*

Schwoebel & Coslett in 2005 proposed two methods for assessing the perception of the metric size and shape of the body: the localization of tactile input delivered to a large mannequin and a Matching Body Parts Task, during which subjects were asked to point to their own body part that was closest to that visually presented. In the last ten years, there has been a growing interest in the characterization of the body model of size and shape (Longo & Morcom, 2016; Longo & Haggard, 2010; Tamè, Braun, Holmes, Farnè, & Pavani, 2016; Tsakiris, 2010). Several tasks have been used to assess the body model. Sposito and collaborators (2010) used the Forearm Bisection Task, in which participants are required to indicate the midpoint of one of their forearms through a ballistic movement performed with the opposite hand. This task has attested the superiority of the representation of body metrics as compared to the representation of extrapersonal objects. Also, the authors showed modulation of body metric due to brain damage and neglect. Sposito and colleagues (2010) found smaller errors when participants bisected their forearm as compared to a cylinder occupying the same space sector. This difference was even more evident for neglect patients, in whom the rightward bisection bias, which is a marker of neglect condition, was reduced in the forearm as compared to solid object bisection.

Furthermore, forearm bisection proved to be sensitive to body representation changes following tool use. When healthy participants reached for objects in far space using a long rake, the authors found a distal shift in forearm bisection (Sposito et al., 2012) compatible with the putative extension of body representation towards the tip of the tool following its skilled use (Maravita & Iriki, 2004). Moreover, in a group of patients showing the pathological behaviour of feeling a sense of ownership towards alien limbs, it was also shown a distal bias of forearm bisection following the mere observation of tool-reaching when performed by the self-misattributed alien limb (Garbarini et al., 2015).

In other experimental procedures typically participants are asked to estimate body size by visual comparing a body segment with a line (Longo & Haggard, 2012b); to localize tactile stimuli or anatomic landmarks based on position sense (Longo & Haggard, 2010, 2012b); or to estimate the distances between tactile stimuli (Longo, Mancini, & Haggard, 2015; Longo & Morcom, 2016; Sadibolova, Tamè, Walsh, & Longo, 2018). The latter task (i.e., Body Distance Task - BDT) relies on both the ability to localize tactile stimulations on the body and to estimate the size of the tactile percept. On the one hand, tactile localization is mediated by a higher-order representation based on somatosensory processes, known as the superficial schema (Head & Holmes, 1911;Longo et al., 2010; Mancini, Longo, Kammers, & Haggard, 2011). On the other hand, tactile size perception is referred to a stored representation of the metric properties of the body, i.e. the body model (Longo, 2015; Longo & Haggard, 2011). The rationale behind this procedure is that, in order to estimate the distance between two touches applied on the skin, we need to map those touches on a mental representation of the body part being touched, a stored model that retains the metric properties of the body (Longo et al., 2010, 2015; Longo & Haggard, 2011, 2012a). The tactile distance perception procedure (Longo & Golubova, 2017) consists of judging the perceived distance between touches applied on the dorsum of participants' hand by reporting the estimations verbally. In the original proposal of this procedure, a 4x4 grid of points is marked on the skin. The rows run along with the medio-lateral hand axis and the columns run along with the proximo-distal one. During testing, two locations are stimulated in sequence by the experimenter, and blindfolded participants make verbal estimates of the perceived distance. Since tactile distance perception relies on both the ability to localize tactile stimulations on the body and to estimate the size of the tactile percept, the task is used to assess the metric perception of body parts. The perceptual features of tactile distance perception task make it a promising method in the characterization of body metric representation (Longo, 2015; Tamè, Azañón, & Longo, 2019). Nevertheless, potential cognitive confounders could be (i) the response estimation being used and (ii) the reliability and replicability of the results.

The literature about tactile distance perception mostly focused on the hand (Longo & Golubova, 2017; Longo et al., 2015; Sadibolova et al., 2018). In particular, Longo and coworkers (2015, 2016) found that participants' metric perception of the hand is distorted as compared to its physical shape revealing a fat, squat hand representation. Longo and colleagues asked participants to estimate with a verbal response the distances between two touches on the body, requesting for an imaginary estimation based on metric size awareness. Stone and colleagues (2018) employed the same experimental procedure on the upper leg. Interestingly, instead of a verbal estimation, they asked participants to estimate the distance between the tactile stimuli by placing the thumb and the index fingers on a touch screen, reproducing the distance between the touches physically. Such a procedure is not useful in the case of distances that cannot be reproduced by the hand (as in the case of spatial distances). The limitation of non-reproducible distances could be overcome providing a visual reference (i.e. a line) for the perceptive recalibration. Nonetheless, a visual stimulus raises additional issues, such as using a proportional reproduction vs the reproduction of the physical length and employing an analogical line vs a discrete line.

So far, the results about the hand and the leg revealed that people underestimate body distances running along the proximo-distal direction independently by the body district (Longo et al., 2015, 2016; Stone et al., 2018). Nevertheless, there is no information about the replicability of the tactile distance task within the same participant. The experimental question in this latter case asked if the misestimation is stable within a participant and thus if this reflects a perceptual bias that can be assessed multiple times. If so, this measure could be used as a reliable procedure to measure changes in body metric representation that may occur because of specific experimental manipulations, pathological conditions or interventions.

Notably, although the distance tasks used with the hand and the legs are the same, data have been processed differently. Longo and collaborators used the Multidimensional Scaling (MDS) and the Procrustes Alignment (PA), two techniques developed for the analysis of perceptual spaces (Frith, Friston, Frackowiak, Fletcher, & Liddle, 2007). Through these techniques they extracted the underlying spatial structure of a set of tactile stimuli applied on the skin. MDS is a descriptive method for representing the structure of a system, and it has been used also with functional neural connectivity (Frith et al., 2007), personality traits (Widiger, Trull, Hurt, Clarkin, & Frances, 1987) and psychiatric symptoms (Olatunji et al., 2015). Longo and collaborators (2017) put together the principal aim of extracting a spatial configuration underlying a set of items and its neuro/psychological applications in order to construct perceptual maps reflecting body metric representation as assessed through tactile perception. Moreover, they compared the perceptual maps obtained with the grid used to perform the task obtaining a dissimilarity index between the two configurations, called the Procrustes Distance. Taking together, MDS and PA consist of statistical shape analyses and can be used to convey information about the perceived spatial distribution of a set of tactile stimuli.

Stone and colleagues (2018), instead of using an index of global shape dissimilarity (i.e. Procrustes Distance), compared the length provided by the participants at each stimuli pair to the actual distance and calculated the percentage of perceived misestimation, using the following equation: "% misestimation= (perceived distance − actual distance)/actual distance∗100". While the Procrustes Distance offers an index of global shape dissimilarity, without discriminating the type of distortion, the percentage of misestimation provides a specific estimation error that can be studied concerning the specific characteristics of the grid, such as the distance between the points or their position. This index is informative about the directional bias: when the Confidence Intervals (CIs) do not include zero, we can conclude for a consistent bias, the direction of which is given by the sign of the CIs. The different procedures give complementary non-overlapping information and should be coupled, instead of being used as alternatives.

To better explain the difference between the global shape dissimilarity and the directional bias, we can imagine two different scenarios, given a square shape to be represented (Figure2, dashed line). In the first scenario (Figure2, first scenario), two participants represent two rectangular shapes with the same amount of distortion but the opposite sign on the horizontal and the vertical axes. Participant 1 underestimates the horizontal axis (-50%) and overestimates the vertical one (+50%). On the contrary, participant 2 overestimates the horizontal axis (+50%) and underestimates the vertical one (-50%). Since both participants show the same shape distortion, the mean Procrustes Distance is higher than zero.

On the contrary, the opposite sign compensates the directional biases. Consequently, the mean percentage of misestimation is 0% on both axes. In the second scenario (Figure2, second scenario), two participants represent two square shapes with different amount of distortion. Participant 1 overestimates both the horizontal and the vertical axis (+50% and +50% respectively). On the contrary, participant 2 reproduces the same shape as the real one (+0% on both axes). Since the shape is always equal to the model, the mean Procrustes distance is zero. On the contrary, the mean percentage of misestimation is the average of the different amounts of distortion produced by the participants (+25% on both axes). These scenarios show that Procrustes Distance and the percentage of misestimation convey different information about the same task.

1st scenario 2nd scenario

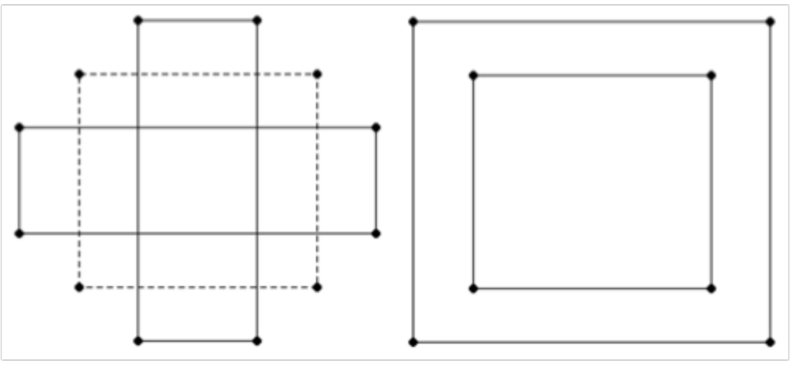

Figure 2. **Examples of scenarios for the comparison between global shape dissimilarity and direction bias.** In the first scenario, Directional bias would be 0, and the global shape dissimilarity would be greater than 0, the opposite is correct for the second scenario, where global shape dissimilarity would be blind to the distortion which can be captured by the Directional bias index.

1.1.2. Plasticity

One important thing that seems to be shared by different aspects of body representation is its plastic nature. Plasticity is a fundamental characteristic of the nervous systems characterized by constant adaptive changes in psychic functions and behaviour (Kolb, et al., 2003).

During our life, these representations change according to different experiences (Flor, Nikolajsen, & Jensen, 2006; Sposito, Bolognini, Vallar, & Maravita, 2012). Body representation is also constantly changing due to both long-term processes, such as development and skill learning, and short-term events, such as movements. Remarkably, not only positive, but also negative plastic changes can occur in the brain, following disease and body part disuse and immobilization (Bassolino et al., 2014; Flor et al., 2006; Hallett, 2001).

Crucially, body representation can be temporarily altered by means of experimental protocols (Gandevia & Phegan, 1999; Giurgola, Pisoni, Maravita, Vallar, & Bolognini, 2019; Tosi, Romano, & Maravita, 2018). Indeed, several studies adopted different experimental procedures, collectively named "bodily illusions", to induce a change in the body representation (Ehrsson, Holmes, & Passingham, 2005; Medina, Khurana, & Coslett, 2015; Pasqualotto & Proulx, 2015; Romano, Bottini, & Maravita, 2013; Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010; Scandola et al., 2014; Tosi et al., 2018). Bodily illusions strongly support the idea that body representation is dynamic and can be modified through the proper balancing of multisensory information.

1.1.3. Body representation disorders

Motor impairments, including hemiparesis and hemiplegia, are the most common deficits after stroke (Schaechter, 2004) and restoration of motor skills is often incomplete. Although rehabilitative arm training positively affects brain plasticity and may have positive effects on recovery (Dohle et al., 2009; Nelles et al., 2001), negative brain plasticity can also occur, leading, in patients with acquired motor deficit, to a reduction of cortical representation of motor areas that go beyond the area directly affected by the stroke (Flor et al., 2006; Hallett, 2001).

Indeed, motor impairments, preventing the regular and active use of the affected limbs, lead to the decrease of the cortical representation of sensorimotor areas of those limbs (Dohle et al., 2009), further affecting limb functionality. This idea, also known as "learned paralysis", was first introduced by Taub and colleagues (Taub et al., 1998) who studied the motor behaviour of surgically deafferented monkeys. The idea of learned paralysis was extended to humans by Ramachandran (Ramachandran, 1993) who suggested that the visual feedback of immobility of the affected limb following motor output, would progressively reinforce the acquired knowledge that the limb cannot move. As a consequence, the representation of that limb in the sensory cortex, lacking from sensory afference, would progressively shrink, while spared neurons would be functionally reorganized, increasing the representation of the adjacent body parts (Hallett, 2001), resulting in increasing disability and enhancing the effects of motor impairment. A similar process has been noticed after amputation, together with a sensation of *telescoping* occurring when the distal part of the phantom is gradually felt to approach the residual limb (Nikolajsen & Jensen, 2001). Such a mechanism can be related to a modified perception of the body metric.

Following brain damage, a person may become impaired in the execution of voluntary actions, in spite of preserved strength. This neuropsychological condition is named Ideomotor Apraxia (IMA) and is commonly defined as the inability to imitate gestures, pantomime gestures or in tool-use (Laurel J. Buxbaum & Randerath, 2018; Canzano et al., 2016; Georg Goldenberg, 1995; Sunderland & Sluman, 2000) due to a disorder of higher-order cognitive functions. Apraxia is commonly observed in patients following lesions in the left-sided parietal and frontal cortices and deep structures (Cantagallo, Maini, & Ida Rumiati, 2012; Goldenberg, 1995; Smania, Girardi, Domenicali, Lora, & Aglioti, 2000a), but cases following right-brain damage have also been reported (De Renzi, Motti, & Nichelli, 1980; Kaya, Unsal-Delialioglu, Kurt, Altinok, & Ozel, 2006).

Apraxic patients may show impairment in different subtypes of movements, and various different classifications have been attempted over time (Buxbaum & Randerath, 2018). An influential theoretical framework for understanding apraxia suggests that apraxia may originate from impaired access to the body schema (Buxbaum, Giovannetti, & Libon, 2000; Canzano et al., 2016; Georg Goldenberg, 1995). This vision intends IMA as a disorder in the interpretation and reproduction of specific bodily configurations rather than a mere disorder of motor sequence (Goldenberg, 1995; Sunderland & Sluman, 2000). In an elegant experiment, Goldenberg showed that patients with apraxia were unable to imitate gestures with their own body, a task requiring the reproduction of bodily configuration and motor sequence. Crucially they were also unable to reproduce a target posture on a life-size mannequin, a task that requires to process bodily configurations, involving a different motor sequence to reproduce it on the mannequin than on one's body (Goldenberg, 1995).

1.2. EMBODIMENT

As stated before, body representation can be temporarily altered by means of experimental protocols (Gandevia & Phegan, 1999; Giurgola et al., 2019; Tosi et al., 2018). Indeed, several studies adopted different experimental procedures to induce a change in the body representation .

The core mechanism accounting for the efficacy of these experimental procedures might be the process of embodiment, which can be defined with the following statement: "(an object) E is embodied if and only if some properties of E are processed in the same way as the properties of one's own body" (de Vignemont, 2011). In its widest definition, the embodiment hypothesis suggests that human physical, cognitive, and social embodiment ground our conceptual and linguistic systems (Rohrer, 2005). In more philosophical terms, it was introduced to overcome the Cartesian dualism between mind (res cogitans) and body (res extensa) (Rohrer, 2005) and corresponds to a specific mode of presentation of the property of an object, which results from a specific way the property is processed (de Vignemont, 2011).

The usual way to assess the experience of embodiment is by means of a questionnaire referring to the subjective sensations of ownership, agency and location referred to external objects (Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008; Romano, Llobera, & Blanke, 2016; van der Hoort, Guterstam, & Ehrsson, 2011). In particular, Longo and collaborators (2008) investigated the structure of embodiment by taking a psychometric approach to the introspective reports of participants experiencing a body illusion. Participants were asked to indicate their agreement with 27 statements, using a 7-point Likert scale. A response of +3 indicated that they "strongly agreed" with the statement, -3 that they "strongly disagreed", and 0 that they "neither agreed nor disagreed". Then they used a principal components factor analysis (PCA), to investigate the latent structure of participants' experience, and to quantify the experience of embodiment. The authors extracted four components. The first one was termed embodiment, and comprised items relating to the feelings that a fake hand (see paragraph 1.2.2. Rubber Hand Illusion) belonged to the participant. The second component, termed loss of own hand, comprised items relating to one's hand disappearing. The third component, termed movement, was comprised of two items relating to the perceived motion of one's own hand, and the fake one. The fourth component was termed affect and included items relating to the experience being interesting and enjoyable. In the control condition, a new component termed deafference appeared and was related to the sensation of numbness in one's own hand. Since the embodiment component accounted for a large portion of the variance, the authors conducted an additional PCA. Three components emerged: ownership related to the feeling that the fake hand was part of one's body; location related to the feeling that the fake hand and one's own hand were in the same place; agency related to the feelings of being able to move the fake hand.

On the other hand, some authors have employed physiological responses such as the Skin Conductance Response (SCR) to capture the effect of embodiment (Ehrsson, Wiech, Weiskopf, Dolan, & Passingham, 2007; Guterstam, Petkova, & Ehrsson, 2011; Romano, Llobera, & Blanke, 2016; Romano, Pfeiffer, Maravita, & Blanke, 2014). These studies indicate that events threatening fake body parts can trigger affective responses (affective resonance) when they are embodied (Ma & Hommel, 2013).

Previous work has studied the process of embodiment by means of tools and illusions. Here we will focus on tool use and three types of body illusion.

1.2.1. Tool use

Tool-use has been found to induce plastic changes in body metric perception resulting in the tool being incorporated in the body representation (Bruno et al., 2019; Cardinali et al., 2009; Romano, Uberti, Caggiano, Cocchini, & Maravita, 2018; Sposito et al., 2012).

In healthy participants, reaching for objects in far space using a tool induces a distal shift in forearm bisection (Sposito et al., 2012). The authors used the Forearm Bisection Task by asking participants to estimate the subjective midpoint of their own forearm before and after a training phase tools. The results showed that participants indicated a more distal midpoint, thus displaying an increased representation of the length of the arm handling the tool.

The same task was used in a more recent study by Romano and collaborators (2018) investigating how different actions with a tool may impact the subjective metric representation of the body. They found a proximal shift in the perceived midpoint when the tool-use mostly involved proximal movements (i.e., shoulders), while a distal shift occurred after a training phase asking for proximal movements (wrist and fingers). These results suggest that the specific motor pattern required by the training can induce different changes in body representation.

Bruno and coworkers (2019) added further arguments to this process of embodiment. The authors compared two types of training of tool use. In the active condition, participants voluntarily accomplish the movement by representing the goal of the action, in the passive condition, the tool-use was produced without any goal representation by means of robotic assistance. Results showed a significant increase in the perceived arm length only after the active task. From a theoretical perspective, these findings suggest that tool-use may shape body metric representation only when action programs are represented and not passively produced.

1.2.2. Rubber Hand Illusion

This illusion consists of a life-sized rubber model of a hand and arm placed on a table directly in front of a subject. The participant's real arm rests upon a table and is hidden from the view with a screen positioned between the fake and the real arm. The subject sits with eyes fixed on the artificial hand while the experimenter used two small brushes to stroke the rubber hand and the subject's hidden hand synchronously (Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005).

Typically, subjects experience an illusion in which they feel the touch of the viewed brush as if the rubber hand has sensed the touch. Moreover, subjects' perception of their real hand is displaced toward the rubber hand (i.e. proprioceptive drift)

Botvinick and Cohen (1998) suggested that the Rubber Hand Illusion (RHI) reflected a three-way interaction between vision, touch, and proprioception. Vision captures touch (i.e. visual capture), resulting in a mislocalization of the tactile percept toward the spatial location of the visual percept. This visuotactile correlation influenced the felt position of one's own hand (Tsakiris & Haggard, 2005). However, the RHI occurs when participants view a compatible rubber hand positioned in a congruent posture that is stimulated synchronously with their own hand. Tsakiris and Haggard (2005) highlight that the illusion does not work when a no-hand-shaped object is stroked synchronously with the real hand. The authors suggest that the concurrent visuotactile inputs have to be integrated within a representation of one's own body to be embodied. The authors suggest that RHI is modulated by bottom-up processes of visuotactile correlation together with top-down influences originating from the representation of one's own body. Indeed, Tsakiris et al (2010) point out the need for an object to preserve precise corporeal features in order to be embodied as one's own body part.

More recently the same illusion has been replicated using robotic hands and virtual reality (Ma & Hommel, 2013; Romano, Caffa, Hernandez-Arieta, Brugger, & Maravita, 2015; Sanchez-Vives et al., 2010). However, in these studies, the proprioceptive drift and the affective resonance have been induced through visuomotor congruency instead of visuotactile inputs.

1.2.3. Mirror Box Illusion

First described in the treatment of phantom limb pain (Ramachandran et al., 1995), Mirror Box Illusion typically consists of a vertical mirror positioned in the centre of a box, holding a sagittal orientation in respect to the patient. The patient places his affected limb/stump behind the mirror and the healthy one in front of it in such a way that the reflection of the healthy limb visually mimics the hidden, affected, limb. Then the patient is asked to perform bilateral movements with the affected and non-affected hands. This procedure typically results in the sensation that both limbs are moving (for a review, see Ramachandran & Altschuler, 2009).

The core mechanism accounting for the efficacy of the mirror box might be the process of embodiment of the patient's healthy hand seen in the mirror, which improves body representation (Liu

& Medina, 2017; Romano, Bottini, et al., 2013). The reflection of the healthy hand seems visually superimposed on the felt location of the phantom, creating the illusion that the phantom has been resurrected (Ramachandran & Altschuler, 2009).

The same process would modulate sensory-motor processing in the hand hidden in the box, as shown in both healthy (Bultitude, Juravle, & Spence, 2016; N. P. Holmes, Crozier, & Spence, 2004; Liu & Medina, 2017; Romano, Bottini, et al., 2013) and brain-damaged participants (Altschuler et al., 1999; Michielsen et al., 2010; Romano, Sedda, et al., 2013; Yavuzer et al., 2008).

Romano and collaborators (2013) suggested that the critical trigger of the perceptual and motor consequences of the MB training may be a "visual capture" effect (Botvinick & Cohen, 1998; Pavani et al., 2000; Holmes et al. 2004) where the visual input, compatible with the hand inside the box, is weighted more than the signals coming from the hidden hand (van Beers et al., 1998). Such a fast-emerging visual capture would favour a process of embodiment of the reflected hand which would conflict with the internal knowledge of the sensory-motor status of the contralateral hand.

1.2.4. Full-Body Illusion

A particular type of illusion is the one induced by the so-called Full-Body Illusion (FBI) in which subjects experience the ownership of another person's body (or parts of it) by seeing it from a first-person perspective (Banakou, Grotenac, & Slater, 2013; Keizer, Van Elburg, Helms, & Dijkerman, 2016; Petkova & Ehrsson, 2008; van der Hoort et al., 2011). In the FBI, participants see a virtual (or filmed) body that receives a tactile stimulation. Congruently with the seen touch, the participant gets a very similar touch on his/her body, inducing embodiment for the seen body (Ehrsson, 2007; Lenggenhager, Tadi, Metzinger, & Blanke, 2007). The FBI has been replicated using congruent visuotactile stimulation, or visuomotor stimulation (Kilteni, Normand, Sanchez-Vives, & Slater, 2012), using a virtual body seen from a first-person perspective (Romano et al., 2016; van der Hoort et al., 2011) or from a third-person perspective (Banakou, Grotenac, & Slater, 2013; Petkova & Ehrsson, 2008; Romano, Pfeiffer, et al., 2014). Recently, Van der Hoort adopted the FBI procedure to induce the embodiment of bodies with different sizes (van der Hoort et al., 2011). Specifically, in their study, they used a life-sized body (180 cm height), a doll's body (80 cm or 30 cm height), or a gigantic body (400 cm height). Pre-recorded videos of the fake bodies stimulated with a stick were presented to the participants through a set of Head-Mounted Displays. The video was coordinated with a synchronized tactile stimulation on participants' legs producing a congruent visuotactile stimulation. The embodiment of the bodies was witnessed by both the questionnaire measuring the subjective experience and by the increase of SCR to an unexpected threat toward the fake body. The authors provided evidence that when participants experience a doll's body as their own, they perceive objects to be larger and farther away than when they are exposed to a normal-sized body. On the contrary, when they experience a giant's body, they interpret the same objects to be smaller and nearer. Similar results have been found using a visuomotor illusion, using a 4-years-old virtual body, presented from a third-person point of view; in this study, participants overestimated the sizes of objects presented after the Full-Body Illusion (Banakou et al., 2013).

These studies suggest that the FBI, can induce a subjective experience of embodiment of different body sizes and that an altered representation of the body affects the perception of an object's size and its location in space. However, besides the subjective report of embodiment, it remains unclear the impact of embodiment on the metric representation of one's own body, i.e. the realistic estimation of the size of one's own body part. Finding an influence of bodily illusion on this measure would illuminate further on the plastic properties of body representation, induced by such brief, yet pervasive, illusory paradigms.

1.3. THE RELATIONSHIP BETWEEN BODY AND SPACE

In order to accomplish most of our daily life activities, we need to move appropriately and effectively with the environment around us. This interaction is mediated by our body, which serves as a reference frame for space perception (Merleau-Ponty, 1945; van der Hoort, Guterstam, & Ehrsson, 2011). As such, our body plays a significant role in the way we interact with the space around us (Holmes & Spence, 2004; Rizzolatti et al., 1997).

In the past few years, many studies have focused on the relationship between body representations and peri-personal space (Holmes & Spence, 2004), defined as the space immediately surrounding our bodies (Rizzolatti et al. 1997). It is represented by populations of multisensory neurons, from a network of premotor and parietal areas, which integrate tactile stimuli from the body's surface with visual or auditory stimuli presented within a limited distance from the body (Noel et al., 2015). Previous findings have demonstrated that the body's characteristic and configuration could influence the way we perceive this space. For instance, Longo and Lourenco (2006) used a Line Bisection Task to investigate the effects of tool-use on space perception, and the nature of the transition between near and far space. Their results suggested that using a tool to modulate arm length perception, also expand the range of near space with a gradual transition into far space. Similarly, when objects are presented as magnified, they appear to shrink back to normal size if a magnified hand is placed next to them. On the contrary, when objects look smaller than they are, the opposite occurs. These findings by Linkenauger, Ramenzoni, & Proffitt (2010) highlight the role of body size in scaling objects' perception.

At a higher cognitive level, there is also evidence that egocentric coordinates, based on a body-centred experience of the environment, define the spatial representations underlying both subject-to-object and object-to-object localization in space (Nori, Iachini, & Giusberti, 2004). The authors asked a group of participants to point to an object in relation to their position (egocentric condition) and another group point to an object in relation to another object (allocentric condition). The results showed no difference between subject-to-object and object-to-object localization, suggesting a preferential role of the body for object perception in space.

1.1.1. Body affordances

The role that the body plays in objects and space perception may also alter the potential interaction of the body with the spatial surrounding. Some studies have investigated the relationship between the body and the intention to perform actions in far space (Fini, Brass, & Committeri, 2015; Proffitt, Bhalla, Gossweiler, & Midgett, 1995; Proffitt, Stefanucci, Banton, & Epstein, 2003). For instance, the perceived dimensions of the body have been shown to affect the estimation of aperture widths (Stefanucci & Geuss, 2009) and the necessary actions adjustments to walking through them (Warren & Whang, 1987). Similarly, the egocentric distance perceived by participants has been reported to increase when the body capabilities are manipulated by asking subjects to carry a heavy backpack (Proffitt et al., 2003); an effect similar to this has also been reported on the perception of geographical slant, which has been shown to preserve the relationship between inclination and behavioural potential (Proffitt et al., 1995).

These studies suggest that also the extrapersonal space (the space outside reaching distance) is perceived in relation to our movement capabilities. An interesting study by Fini, Brass, & Committeri (2015) investigated the categorization of distance in extrapersonal space using human or non-human allocentric reference frames. Subjects were asked to categorize as “Near” or “Far” a target object placed at progressively increasing or decreasing distances until a change from near to far or vice versa was reported. They found a significant extension of the near space when the reference was a human virtual agent instead of an object. The same result was not replicated with a wooden dummy or a human virtual agent tied to a pole, thus reducing movement potentialities. These results confirmed that during allocentric distance judgments within extrapersonal space, we implicitly process the movement potentialities of the reference frame.

Altogether, these findings highlight the critical role of a proper body perception for efficient interaction between individuals and their spatial surroundings. Nevertheless, it is not clear if the representations of the body could influence our perception of far extra-personal space. Our hypothesis is that embodiment can shape our perception of body metric, also influencing space perception.

2. EXPERIMENT 1. VALIDITY AND REPLICABILITY OF A BODY ILLUSION USING DISTORTED VISUAL FEEDBACK FROM THE BODY[1]

2.1. INTRODUCTION

In the present experiment, we used a visuo-tactile Full-Body Illusion-like paradigm (FBI) provided with a new, portable, technological setup, to assess the feasibility and the replicability of the BI for body parts of different sizes, controlling for the role of visual perspective in the illusory embodiment. We tested whether it is possible to induce and replicate, in the same participant, the embodiment toward mannequins of different sizes through a novel Full-Body Illusion-like paradigm using a head-mounted displays.

2.2. MATERIAL AND METHODS

2.2.1. Participants

20 healthy volunteers took part in Experiment 1 (15 females; mean age = 22.7±3.0, range 18-27; mean education = 16.1±2.0, range 13-19). All participants had normal or corrected to normal vision and were naive to the purpose of the experiment. All participants gave their written informed consent before participating in the experiment. The study was approved by the local Ethics Committee "Commissione per la Valutazione della Ricerca, Dipartimento di Psicologia" of the University of Milano-Bicocca and was conducted by the ethical standards of the Declaration of Helsinki (World Medical Organization, 1996).

The experimenter explained to the participants the general aim of the study and the procedure before collecting the informed consent. At the end of the experimental sessions, the experimenter also described the specific scope of the experiment.

2.2.2. Procedure

The experiment consisted of two identical sessions separated by a week that served as a washout period. In each session, participants underwent a BI procedure, induced through a set of Head-Mounted Displays (HMDs – Samsung Gear VR 2016, Samsung Electronics, field of view = 101°) in which they saw pre-recorded videos of three artificial bodies recorded from a first-person perspective. We measured the embodiment with two approaches. We registered phasic skin conductance to a threatening stimulus, as a physiological index of embodiment (van der Hoort et al., 2011), and we administered a questionnaire to obtain a measure of the subjective conscious experience of the illusion. The questionnaire was composed ad hoc with a collection of statements taken from previous studies (Longo et al., 2008; Petkova & Ehrsson, 2008; van der Hoort et al., 2011) and modified for the current setup.

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[1] This chapter is extracted from the paper by Tosi, G., Romano, D., Maravita, A. I am the meter. The representation of one's body size affects the perception of tactile distances on the body (in preparation)

Full-Body Illusion

Participants sat in an armchair, keeping their arms behind the back of the chair. During the procedure participants wore a set of Head-Mounted Displays in which they saw pre-recorded videos (encoding: MPEG-H Part2/HEVC (H.265), resolution: 2560x1280, 30 fps) of three artificial bodies receiving a tactile stimulation with a stick (induction phase) and later stung by a syringe with the needle clearly visible (to measure the evoked response to threat). Videos were recorded with a 360° camera (Samsung Gear 360 (2016) - camera resolution:15.0 x2MP; features: CMOS, f/2.0; video recording resolution: Near 4k1; processor speed, type: Dual-Core) so that it was possible for the participant to visually explore the environment during the video presentation. Indeed, the 360° videos were recorded in the same room where the experiment was actually performed, and from the very exact position of the participant's viewpoint, providing an immersive, realistic and ecological context. During the experiment, participants were invited to look down at their legs and lower abdomen to increase the focus on the fake body.

The mannequins presented with the same size for the upper body (i.e., they weared a t-shirt of a Medium size), and three different sizes for the artificial pairs of legs: a life-sized pair (108 cm long), a big pair, two time longer (203 cm), and a small pair, half shorter (49 cm). In each video, participants saw one of the three artificial bodies from a first-person perspective, touched by a wooden stick for 120s (see Figure 3 for the setting). Touches were delivered on the upper left leg for two minutes at a frequency of 1 Hz. During this period, the experimenter touched the participant's left leg simultaneously in the corresponding location, generating a synchronous visuotactile stimulation. At the end of this stimulation, a syringe appeared in the video, stinging the artificial leg in order to generate the arousal response which was measured through skin conductance. The sequence of the video including the syringe threat was lasting 15 seconds and started exactly 125 seconds after the beginning of the video. In total, the video length was of 140s. During the video presentation, participants wore headphones delivering white noise, to avoid any acoustic interference.

Participants underwent two conditions of legs orientation. The 0° rotation provided the videos of a body seen from an anatomical viewpoint. This one was our experimental condition for which we expected to induce embodiment. In the 0° rotation, when participants looked down, they saw the mannequin legs holding the same posture of their real legs. In the second condition, we provided the same videos from a 45° counter clock-wise rotated angle. With this arrangement, when volunteers looked down, they saw two legs that were not aligned with their own body, resulting in a non-anatomically compatible viewpoint. We used this non-anatomical orientation as a control condition (Guterstam et al., 2011; Pavani, Spence, & Driver, 2000; Romano et al., 2016). Since previous studies suggested that embodiment only occurs with objects that preserve informative corporeal structural

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features (Tsakiris et al 2010; Tsakiris and Haggard, 2005), we did not use any non-bodily stimulus of control.

By crossing the variables size and viewpoint, we obtained six different conditions: Standard-anatomical; Standard-non-anatomical; Small-anatomical; Small-non-anatomical; Big-anatomical; Big-non-anatomical. In each session, participants experienced all the six conditions in a randomised order. The same sequence was administered in both sessions so that if in the first session a participant did the big-non-anatomical condition as initial condition, this would be presented as the first condition also in the second session.

The entire Experiment 1 result in a 2 (Session) *3 (Size) *2 (Orientation) full factorial, within-subject design.

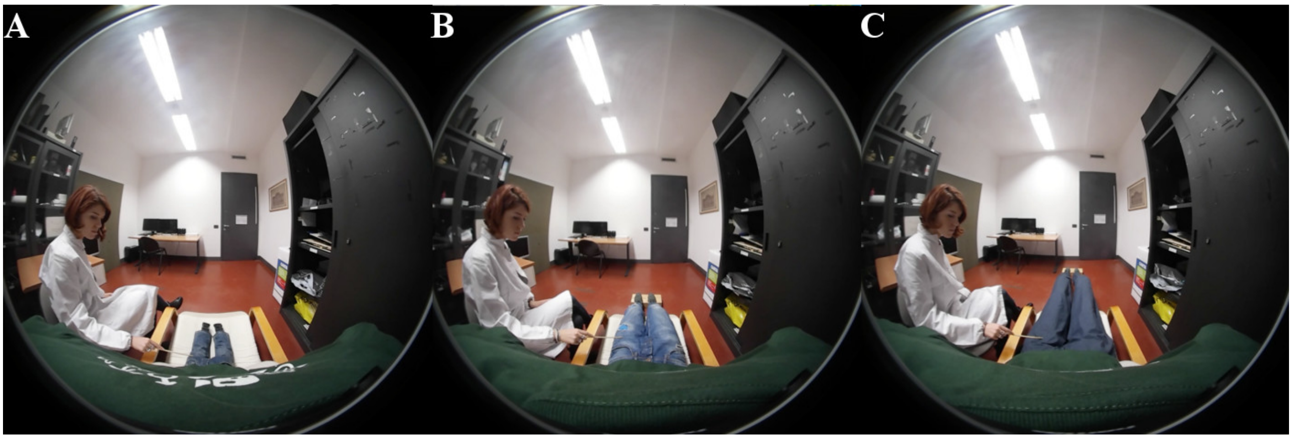

Figure 3. **Body Illusion setting for the anatomical condition. Panel A:** small legs; **panel B:** standard legs; **panel C:** big legs

Skin Conductance

Skin Conductance Level (SCL) was recorded during all conditions in order to capture the level and the variability of sympathetic activity. We recorded the skin conductance of participants with a Biopac System MP150 (Goleta, USA), adopting the module dedicated to Skin Conductance recordings named GSR100c. The electrodes of the transducer (TSD200) were attached to the third phalanx of the participant's index and middle fingers of the left hand. Data were digitalized at a sample rate of 100 Hz; the gain parameter was set at 5µmho/V. The acquired signal was processed offline with the Biopac software Acknowledge for Windows (Version 4.2).

The signal was pre-processed in 2 steps to obtain phasic changes of the skin conductance (i.e., the Skin Conductance Response – SCR): a) off-line smoothing of the signal (mean with gaussian distribution of 25 samples); b) high pass filtering at .05 Hz.

We then extracted two indices for each condition. First, we calculated the SCR Peak-to-Peak (Petkova & Ehrsson, 2008; Romano et al., 2016; van der Hoort et al., 2011) evoked by the syringe illusory prick. This measure was computed as the difference between the maximum and the minimum

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value detected in the time window of 10 seconds starting with the appearance of the syringe. We then applied a log transformation to the data to improve the fit with normal distribution and reduce the impact of extreme values on the inferential statistics. Participants exceeding three standard deviations after the log transformation have been treated as outliers and then excluded from the analysis. A total of three participants were excluded for this reason from the SCR peak-to-peak analysis. Second, we calculated the non-specific fluctuation count (NSFC) during the first 120s of each video (i.e., the induction phase of the illusion). The NFSC is defined as the number of spontaneous response peaks detected in an extended period. A spontaneous response is recorded if the increase of spontaneous phasic activity surpasses the threshold of .05 microsiemens. Acqknowledge software has an automated algorithm to identify those kinds of responses off-line on the acquired signal.

Embodiment questionnaire

After each condition, participants completed a questionnaire about the subjective sensations felt during the video presentations. The questionnaire was adapted from previous studies about body illusions (Petkova & Ehrsson, 2008; van der Hoort et al., 2011) and pain perception in bodily illusions (Romano et al., 2016; Romano, Pfeiffer, et al., 2014). Participants rated their agreement on 16 questions on a seven-points Likert scales where -3 correspond to the less agreement and +3 the most agreement with the statement. Six items were designed to capture the three components of the general experience of embodiment (Longo et al., 2008). The sense of ownership (i.e., the perception that an external object is part of one's body – statements Q1, Q2). The sense of agency (i.e., the feeling of being able to move and control the object as a part of the body – statements Q3, Q4). The sense of location (i.e., the sensation that the object and the body are situated in the same place – statements Q5, Q6). Four statements were designed to capture the sense of "loss of their own legs" (Q7, Q8, Q9, Q10). Moreover, one item (Q11) was intended to catch the illusory feeling of deafferentation, while two control statements (Q12, Q13) were designed to control for task compliance and suggestibility. Two questions about the perceived size of the virtual body and the stick were added with the specific purpose of investigating the subjective modification of perceived visual size of environmental items (Q14, Q15) and a statement (Q16) was designed to capture pleasantness of the whole procedure (see in Appendix Table 1 for the full list of the items).

Responses of each participant were ipsatized (i.e., within-subject normalisation) by centring the responses on the average rate of all the questions in all the conditions and dividing the centered value by the standard deviation of the entire set of responses. Following this procedure, questionnaire data are free from the response set bias (i.e., the response style of each participant) so that each item becomes coded in terms of standard deviations from each participant's average response (Hofstede, 1980).

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2.3. ANALYSIS

We conducted all the analysis with the software JASP 0.8.4 (Jasp Team, 2017). We ran a series of independent repeated measures analysis of variance (rmANOVA) with a within-subject design that encompassed a 2 (Session) *3 (Size) *2 (Orientation) full-factorial model. Significant effects have been interpreted inspecting 95% Confidence Intervals.

In order to evaluate the embodiment of the fake legs from a physiological point of view, we analysed both the Peak-to-Peak and the NSFC measures with two independent rmANOVAs.

To examine the subjective experience of embodiment we applied the same rmANOVA design to the questionnaire data. In particular, we clustered the items referring to the experiences of ownership (Q1, Q2), agency (Q3, Q4 reversed), and location (Q5, Q6) in the main component of the embodiment experience as proposed by Longo and collaborators (2008).

2.4. RESULTS

SCR

Peak-to-Peak. We found a significant main effect of session (F(1,14)= 10.64, $p \leq .05$, η^2= .43), with lower values in the second session (CI: -0.01; 0.16) as compared to the first one (CI: 0.23; 0.39). No further significant effects emerged (all other p-values > 0.11).

NSFC. We did not find any significant effect (all p-values > 0.10). When considering only the first session, a significant trend emerged for the factor size (Small-anatomical (CI: 2.13; 5.43) and Small-non-anatomical (CI: 2.73; 6.77) < Standard-anatomical (CI: 2.80; 6.09) and Standard-non-anatomical (CI: 2.16; 5.01) < Big-anatomical (CI: 3.18; 6.48) and Big-non-anatomical (CI: 3.13; 6.43). However, the result was marginally significant (Size (F(2,34)= 2.74, p= .079)), and these observations should be considered very cautiously.

Embodiment questionnaire

We found a significant main effect of Size (F(2,38)= 30.23, $p \leq .001$, η^2= .61), as well as Orientation (F(1,19)= 21.39, $p \leq .001$, η^2= .53) (Figure 4). These results revealed greater embodiment values in the anatomical condition with the bigger (CI: 0.18; 0.55) and the standard legs (0.51; 0.88). On the contrary, in the non-anatomical condition (big (CI: -0.39; 0.00); standard (CI: 0.17; 0.20) and with the smaller legs (anatomical (CI: -0.46; -0.09); non-anatomical (CI: -0.79; -0.42), subjects always showed weak-to-none embodiment sensations. We also found a trend for interaction: Size * Orientation (F(2,28)= 2.92, p = 0.07). No further significant effects emerged (all other p-values > 0.22).

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The results obtained from each specific factor of the questionnaire are reported in Table 2 in the Appendix.

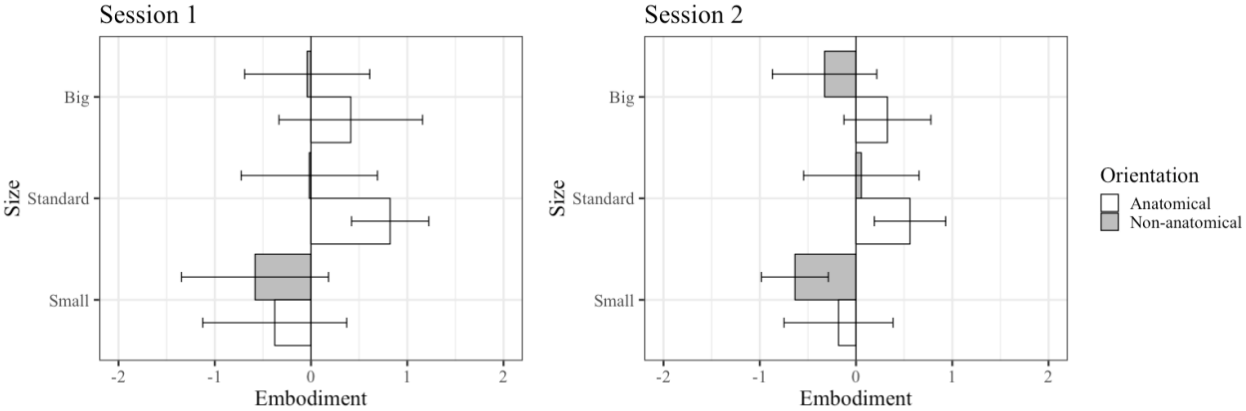

Figure 4. **Results of the rmANOVA on the averaged ipsatized answers to the embodiment statements.** The two panels show Session 1 and 2 of all the Sizes (from the top: Big, Standard, and Small size). Grey and white column display respectively Non-anatomical and Anatomical conditions.

2.5. CONCLUSION

We found a significant difference between the first and the second session in the SCR Peak-to-Peak (P-P), with decreasing values in the second one. Notably, the P-P, is susceptible to habituation, so that participants that may have already familiarised with the task and the procedure, tend to respond less prominently for the appearance of the syringe in the second session. We did not find any significant change of skin conductance because of Size or Orientation, suggesting that we have no evidence to sustain a difference induced by the embodiment or body size at the physiological level of response, neither for the SCR P-P nor for the NSFC. The lack of modulation in SCR could be due to the poor number of threatening stimuli since we administered only one puncture after each condition. In the first session, we found a positive trend for the factor size in the analysis of the NSFC, showing a higher number of events during the videos of the big legs and a decreasing number of SCR along with the reduction of the legs' length. It is crucial however to note that the results of SCR were dubiety significant so that any comment should be considered cautiously. Future research may focus on understanding the underlying mechanisms of the physiological response to illusory threat and pain perception after the embodiment or disembodiment of body parts (Ma & Hommel, 2013; Romano, Gandola, Bottini, & Maravita, 2014; Romano et al., 2016; Romano, Sedda, et al., 2013; Yuan & Steed, 2010).

Regarding the questionnaire, the main effect of Orientation confirmed our expectations, inducing a stronger embodiment in the anatomical condition than in the non-anatomical one. Moreover, we found a significant effect of Size, obtaining comparable embodiment scores with the big and the standard legs which were both more embodied than the small ones. In the short legs condition, participants always exhibited weak embodiment ratings, both from an anatomical and a non-anatomical

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viewpoint. Interestingly, when the standard size legs were presented in an anatomical perspective, participants were able to process them as part of their body, since there was no difference between the visual input and their body perception. Remarkably, we found the same effect of subjective experience of embodiment with the artificial 203cm length pair of legs.

Embodiment can be defined as the attribution of some properties of an external object to one's own body (De Vignemont, 2011). In this theoretical framework, the FBI would create a contrast between the perception of participants' legs and the visual feedback of compatible longer limbs. In this conflicting situation, the visual capture from the 360° videos would overwrite to some extent proprioceptive and somatosensory information, resulting into the embodiment of the fake legs (Pavani, Spence, & Driver, 2000; Romano et al., 2013a). On the contrary, when the body was presented turned 45° counter clock-wise, the incongruence between participants' position and the non-anatomical rotation of the legs prevent the embodiment even in the presence of synchronous visuotactile stimulation. Experiment 1 results are in line with the previous literature of embodiment of body parts with different sizes (Mancini et al., 2011; Romano et al., 2016; van der Hoort et al., 2011).

Our results suggested that we are more prone to incorporate normal size or bigger bodies, than smaller ones. The lack of embodiment for the small size body has been previously reported in the literature (Marino, Stucchi, Nava, Haggard, & Maravita, 2010; Pavani & Zampini, 2007; Romano et al., 2016). A speculative explanation for this effect is that the body always increases the size along its ontological development. It is possible that our cognitive functions are more willing to accept an enlargement of body size, rather than a reduction, accounting for a top-down influence on the embodiment (Pavani & Zampini, 2007).

Finally, and crucially to the purpose of our study, we did not find any effect of Session, suggesting that the FBI induced with our setup is replicable in the same participants more than once at the level of subjective experience. In contrast to the SCR results, the questionnaire did not show any habituation effect: subjects reported the same embodiment sensations in the first and the second session.

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3. EXPERIMENT 2. THE LONGER THE REFERENCE, THE SHORTER THE LEGS: HOW RESPONSE MODALITY AFFECTS BODY PERCEPTION[2]

3.1. INTRODUCTION

The aim of this study was to consolidate and validate the tactile distance estimation procedure (Body Distance Task – BDT). The reason is that the experimental procedure proposed by Longo (2017) and replicated with a different estimation method by Stone (2018) might be biased by specific cognitive processes that are related to the response modality instead of a perceptual bias (i.e., inability of converting distances in numbers, anchoring effect to a previous response, difficulties in perceptive recalibration). Additionally, the authors (Longo & Golubova, 2017; Stone et al., 2018) used two scoring indeces that have never been compared directly. We assessed this possibility by collecting the estimation with three different modalities (see Materials and methods). Additionally, we analysed the data by calculating both the Procrustes Distances and the Misestimation score thus providing a solid methodological validation to both the methods of collecting the estimates and the way to analyse the bias.

3.2. MATERIAL AND METHODS

3.2.1. Participants

24 subjects participated in the study (23 females, mean age: 24.46±4.33; mean school age: 16.42±1.56). All participants had normal or corrected to normal vision and were naive to the purpose of the experiment. All participants gave their written informed consent before participating. The study was approved by the local Ethics Committee "Commissione per la Valutazione della Ricerca, Dipartimento di Psicologia" of the University of Milano-Bicocca and was conducted following the ethical standards of the Declaration of Helsinki (World Medical Organization, 1996). The general aim of the study and the procedure were explained to participants before collecting the informed consent; participants were informed that the experiment was aimed to study body perception and that they would undergo two experimental sessions. At the end of the study, the specific scope of the study was explained.

3.2.2. Procedure

The experiment consisted of two sessions with one week washout in between. During each session, participants underwent a Body Distance Task, modified from previous studies (Longo & Golubova, 2017; Longo & Haggard, 2012a; Longo et al., 2015) in order to investigate a possible

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[2] This chapter is extracted from the paper by Tosi, G. & Romano. The longer the reference, the shorter the legs: how response modality affects body perception (under review).

distortion of the metric representation of the leg, and they were asked to answer with different modalities.

Body Distance Task

A 3x3 grid of points (see Figure 5, left panel) was stuck on the upper left leg. Before starting, the length of the leg, from the hip (anterior part of the iliac crest) to the knee (inferior part of the kneecap) was measured in order to fix the grid at the centre of the leg. Adjacent points on the grid were separated by 5 cm; rows and columns points ran along the medio-lateral and proximo-distal leg axes respectively. On each trial, two locations were stimulated in sequence, with an inter-stimulus interval of approximately one second. Tactile stimulations were manually applied using a knitting needle with a blunt end of 0.6 mm (size 6); the experimenter touched each point for about one second. There were 36 possible pairs of nine stimuli locations and two orders of presentation for each pair. For example, for the pair AB, the experimenter could touch first the point A and then the point B (AB order) or the other way around: first the point B and then the point A (BA order). The resulting amount of trials was 72 pairs.

In order to collect the perceptive distance between each pair of points, we asked to answer with different modalities. We used the same imaginary estimation proposed by Longo (2015, 2016): after each trial, participants verbally estimated the perceived distance between the two stimuli locations. Besides this verbal response (in cm), which is supposed to be mediated by metric size awareness, we requested for perceptual estimations, which are supposed to rely mostly on visuo-tactile integration. We tried to overcome the limitation of non-reproducible distances providing a visual reference for the perceptive recalibration.

We presented a reference line onto which indicate the perceived distance (Figure 5, right panel). Because the visual stimulus may influence the judgment, we manipulated the reference line providing it in two sizes (15cm and 30cm) and to be used in two ways (analogic or discrete). We asked participants to provide distance estimation considering a range between 0cm and 15cm, but we presented on a computer screen either a 15cm or 30cm line. In the first condition, the reference length corresponded to the actual one presented (15cm), while in the second condition, participants were asked to rescale the line (30cm) to the reference length of 15cm, so that basically they had to double the perceived distance on the line. By doing so, we addressed the influence of a proportional rescaling. We hypothesised that if they used the line just as response modality this additional cognitive process would not affect their estimations. On the contrary, if they used the line as a real reference to represent the distance, we would expect a lower precision with the 30cm line. Moreover, we were interested in evaluating if a discrete scale could improve participants' precision, as compared to an analogic one. On the analogic lines, both for the 15cm and the 30cm length, we provided only the starting and the ending points (0cm

[2] This chapter is extracted from the paper by Tosi, G. & Romano. The longer the reference, the shorter the legs: how response modality affects body perception (under review).

and 15cm) without any other break or cue. Subjects were requested to point at the line at the corresponding perceived distance (analogic condition). To test the discrete scale, we provided participants with the lines with breaks every 0.5cm (in the case of the 15cm line) or 1cm (in the case of the 30cm line). In order to avoid any explicit reference to numbers, only the extremities were indicated with 0cm and 15cm, while the other 28 landmarks in between consisted of symbols (discrete condition). Participants were asked to verbally indicate the symbol corresponding to the perceived distance (Figure 5, on the right). The rationale is that, by providing visual anchors for the judgment, participants would be more precise reporting proportional differences than without anchors, resulting in a more precise measure with less variability across individuals.

The experiment consisted of two sessions: in each session, we presented one of the two lengths (15cm/30cm) for both the analogic and the discrete line, in a counterbalanced order. We also counterbalanced the order of presentation of the analogic and the discrete conditions during each session across participants. Only after the visual responses, participants were asked to answer verbally (verbal condition). We administered the verbal condition either in the session that included the 15cm lines and the one with the 30cm lines, predicting no difference between the two sessions (i.e., no priming of the line length that precedes the verbal response).

This procedure resulted in 6 conditions that combined response modality and line length (Analogic-15cm line, Analogic-30cm line, Discrete-15cm line, Discrete-30cm line, Verbal-15cm line, Verbal-30cm line).

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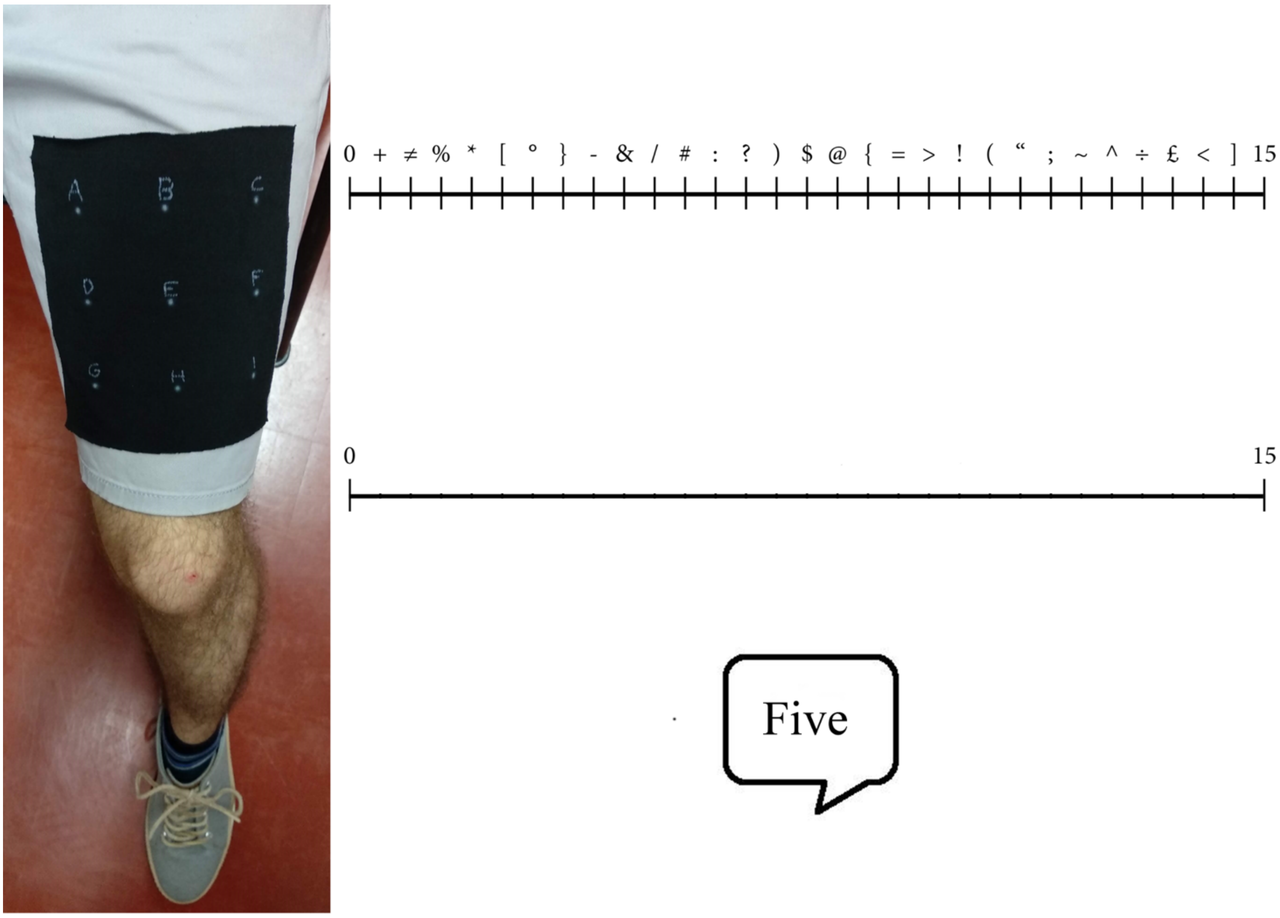

Figure 5. **Setting.** The 3x3 grid of points (10x10cm) used to administer the stimuli for the BDT was stuck on the upper left leg of the participant. In the right panel, the three response modalities used in the experiment – i.e. the discrete line, the analogical line and the verbal response – are depicted

BDT – Global shape dissimilarity. Multidimensional Scaling (MDS) is a method for extracting the spatial structure underlying a set of items given a matrix of pairwise distances between objects (Cox & Cox, 2001; Everitt & Rabe-Hesketh, 1997; Shepard, 1980). For each participant and condition, we constructed a symmetric matrix reflecting the pairwise perceived distances between pairs of points, with zeros on the diagonal (we averaged the distances expressed in the two orders of presentation of the same pair). By applying MDS to the distance matrix we obtained the coordinates of each point of the grid, in a bi-dimensional space, and reconstructed a perceptual configuration of the grid for each subject in each condition. In order to compare the perceptual grid of each participant and the actual one, we used a Procrustes Alignment procedure (Rohlf & Slice, 1990; Goodall, 1991), explained in the Introduction section, which superimposes two spatial configurations of homologous landmarks by translating, scaling, and rotating them to be as closely aligned as possible (Longo & Golubova, 2017). This procedure removes all non-shape differences (Bookstein, 1991) and provides a dissimilarity index between the two configurations, called the Procrustes Distance (i.e., the square root of the residual sum of squared distances between pairs of homologous landmarks which is not removed by Procrustes

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alignment). This measure ranges between zero, if two configurations have the same shape, and one, when they do not share spatial structure at all.

BDT – Misestimation. We compared the length estimated by the participants at each pair of stimuli to the real gap, and we calculated the percentage of perceived misestimation, using the following equation: % misestimation = (perceived distance − actual distance)/actual distance ∗ 100. Since the misestimation additionally measures length judgment errors, independently by the shape of the grid, it represents a complementary index to the Procrustes Distance. Previous studies (Longo et al., 2015; Longo & Morcom, 2016; Stone et al., 2018) have found different rates of distortion for distances running along the longitudinal (proximo-distal) or transversal (medio-lateral) axes. For this reason, we considered the direction of the tactile stimuli (medio-lateral axis/proximo-distal axis), their distance (near-5cm/far-10cm) and the order of presentation of the stimuli (AB order/BA order) in the analysis of the misestimation.

3.3. ANALYSIS

We analysed data with R 3.4.2 (R Development Core Team 2008) and JASP 0.8.4 (Jasp Team, 2017). More specifically, to run MDS we used the packages *stats* (function *cmdscale*), Procrustes Distance have been calculated with the package *vegan* (function *procrustes*). Misestimation percentage have been calculated with ad hoc formula in R. Model comparisons have been ran in R and we used the loglikelihood criteria and chi-squared statistic to select the best fitting model. Bayesian statistics have been running in JASP 0.8.4 (Jasp Team, 2017).

BDT – Global shape dissimilarity. For each condition, we ran a Bayesian one sample t-test on the mean Procrustes Distance. We adopted default parameters, namely the estimation started from a non-informative prior with a Cauchy distribution with a scale of .707. The Bayes-Factor (BF) produced by the Bayesian t-test indicates how much the evidence (i.e., the data) shifted the probability in favor of the null (H0) or the alternative (H1) hypotheses. BF_{10} is the proportion of how many times is more likely that the tested conditions are different (H1) than that they are equivalent (H0). This procedure does not indicate whether one hypothesis is true or false, but which hypothesis is most likely to explain the data. A value of 1 indicates that both the hypotheses describe the data with the same probability, i.e. the test falls in an area of uncertainty and more information is needed to reach a decision. Evidence in favor of the alternative hypothesis would have $BF_{10} > 1$ while evidence in favor to null hypothesis would have a $BF_{10} < 1$. Although a standard is not unequivocally defined, the JASP team suggests the following parameters for interpretation. A factor below 3 indicates anecdotal or null evidence in support of the hypothesis. A BF_{10} of 3 or greater indicates moderate evidence in favor of the alternative hypothesis, while a factor greater than10 indicates strong evidence (e.g. a $BF_{10}=12$ means that it is 12

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time more probable that the two conditions are different than equal, suggesting strong evidence in favor of H1).

Moreover, we conducted a Bayesian Repeated Measure ANOVA with Response (Analogic/Discrete/Verbal) and Line Length (15/30) as within-subjects factors, and the line presented in the first session (15/30) as between-subjects factor. We wanted to evaluate the replicability of the procedure and if different testing modalities affected the shape of the perceptive grid. We performed a model selection, based on the Bayes Factor and we discussed the best fitting model.

BDT – Misestimation. We also ran an additional model comparison between Linear Mixed Model (LMM) ANOVA on the percentage of misestimation. We considered as possible fixed effect factors Session (I/II), Response (Analogic/Discrete/Verbal) and Line length (15/30). We sat participants as random effect variable and we calculated the 95% Confidence Interval (CIs) for the significant effects emerged in the bets fitting model. Finally, we conducted a series of model comparisons on the misestimation and ran an Analyses of Variance (ANOVA) on the best model in each condition independently.

Correlation analyses. To compare the similarity between the two indices (i.e. Global shape dissimilarity and Misestimation) we ran a series of Bayesian correlation analysis calculating the Pearson's r and the Bayes Factor between the response conditions (averaging across 15cm and 30cm lines) and the line length (averaging across the type of response).

3.4. RESULTS

BDT – Global shape dissimilarity. The Bayes Factors reported in Table 1 show a strong evidence in favour of the alternative hypothesis, suggesting a difference between the real and the perceptive configurations in all the conditions considered. Figure 6 shows the differences between the real grid (dashed line) and the mean of the subjects' perceptive responses (solid line) in each condition.

The model selection reported in the Appendix (Table 3), shows that the best fitting model is the null one, suggesting that our manipulations did not influence the global shape dissimilarity significantly.

	mean	**se**	**bf_{10}**	**error %**
Analogic-15cm line	0.32	0.02	6.113e+10	1.685e-13
Analogic-30cm line	0.31	0.01	9.425e+13	3.959e-17
Discrete-15cm line	0.33	0.03	4.078e+7	6.866e-13
Discrete-30cm line	0.30	0.02	5.271e+11	9.359e-18
Verbal-15cm line	0.33	0.03	1.616e+7	6.762e-12
Verbal-30cm line	0.32	0.02	1.220e+10	5.061e-15

***Table 1.* Results of the independent Bayesian one sample t-tests on the Procrustes Distances**. The Bayes Factors show a strong evidence in favour of the alternative hypothesis, suggesting a difference between the real and the perceptive configurations in all the conditions considered.

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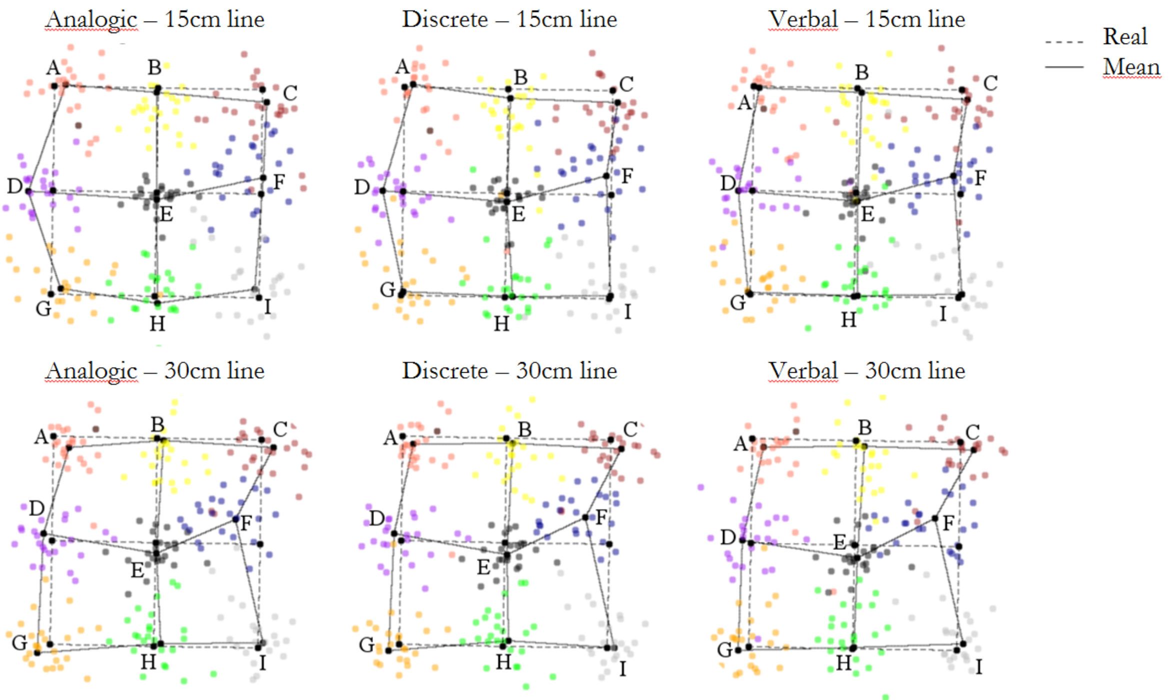

Figure 6. **Results of the Multidimensional Scaling for each condition**. The solid line grid represents the mean of the participants' subjective responses compared with the actual grid (dashed line). We characterized with different colours the perceived location of each of the nine landmarks by each participant on different trials.

BDT – Misestimation. The model selection reported in Appendix (Table 4) shows that the best fitting model is the complete one, including Session, Response and Line length. The complete model revealed significant effects of Session (F(1,10323)= 241.38, p ≤ .001) Response (F(2, 10323)= 262.19, p ≤ .001) and Line length (F(1, 10323)= 525.97, p ≤ .001, and the interaction effects between Session and Response (F(2, 10323)= 47.30, p ≤ .001) and between Line length and Response (F(2, 10323)= 90.05, p ≤ .001). We also found a three-way interaction between Session, Line length and Response (F(2, 10323)= 48.26, p ≤ .001) as shown in Figure 7 (upper panel). Despite an overall underestimation of distances, responses provided on a 15cm line were more accurate (CI: -44.25; -21.45), as compared to the 30cm line (CI: -55.15; -32.07) independently by the type of the line (analogic/discrete). Moreover, in the first session, the verbal response seemed to be more precise (CI: -37.19; -10.26); as compared to the analogic (CI: -50,63; -29.33) and discrete ones (CI: -50.83; -29.23). In the second session, we identified almost the same pattern, except that the Verbal condition after the 30cm line, was found to have a larger underestimation of distances (CI: -52.61; -33.57).

Taking into account each condition separately, we considered the significant effects emerged in each best fitting model (see Appendix, Table 5). We found a significant main effect of Direction in all conditions showing a greater reduction in proximo-distal distances compared to the medio-lateral axis (Analogic 15cm line: Proximo-distal axis (CI: -48.47; -26.34); Medio-lateral axis (CI: -42.23; -20.31); Analogic 30cm line: Proximo-distal axis (CI: -62.58; -43.55); Medio-lateral axis (CI: -58.55; -37.67); Discrete 15cm line: Proximo-distal axis (CI: -49.79; -25.07); Medio-lateral axis (CI: -43.96; -19.95);

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Discrete 30cm line: Proximo-distal axis (CI: -62.87; -43.98); Medio-lateral axis (CI: -58.21; -37.44); Verbal 15cm line: Proximo-distal axis (CI: -43.95; -18.12); Medio-lateral axis (CI: -38.84; -12.89); Verbal 30cm line: Proximo-distal axis (CI: -47.25; -22.98); Medio-lateral axis (CI: -41.36; -11.83)) as shown in Figure 7 (lower panel). Moreover, we detected a significant main effect of Distance in the Analogic-15cm line [F(1,834)= 9.72, p ≤ .05]), Discrete-15cm line [F(1,838)= 10.65, p ≤ .001]), and Verbal-30cm line [F(1,838)= 12.09, p ≤ .001]. However, the direction of the effect was not clear, since we found a greater reduction for the short distances than for the big ones with the Analogic-15cm line and the Discrete-15cm line, and the opposite pattern with the Verbal-30cm line. Finally, we found a significant interaction effect between Direction and Order with the Analogic-15cm line [f(1,834)= 8.46, p ≤ .05] and the Verbal-15cm line [F(1,837)= 6.34, p ≤ .05].

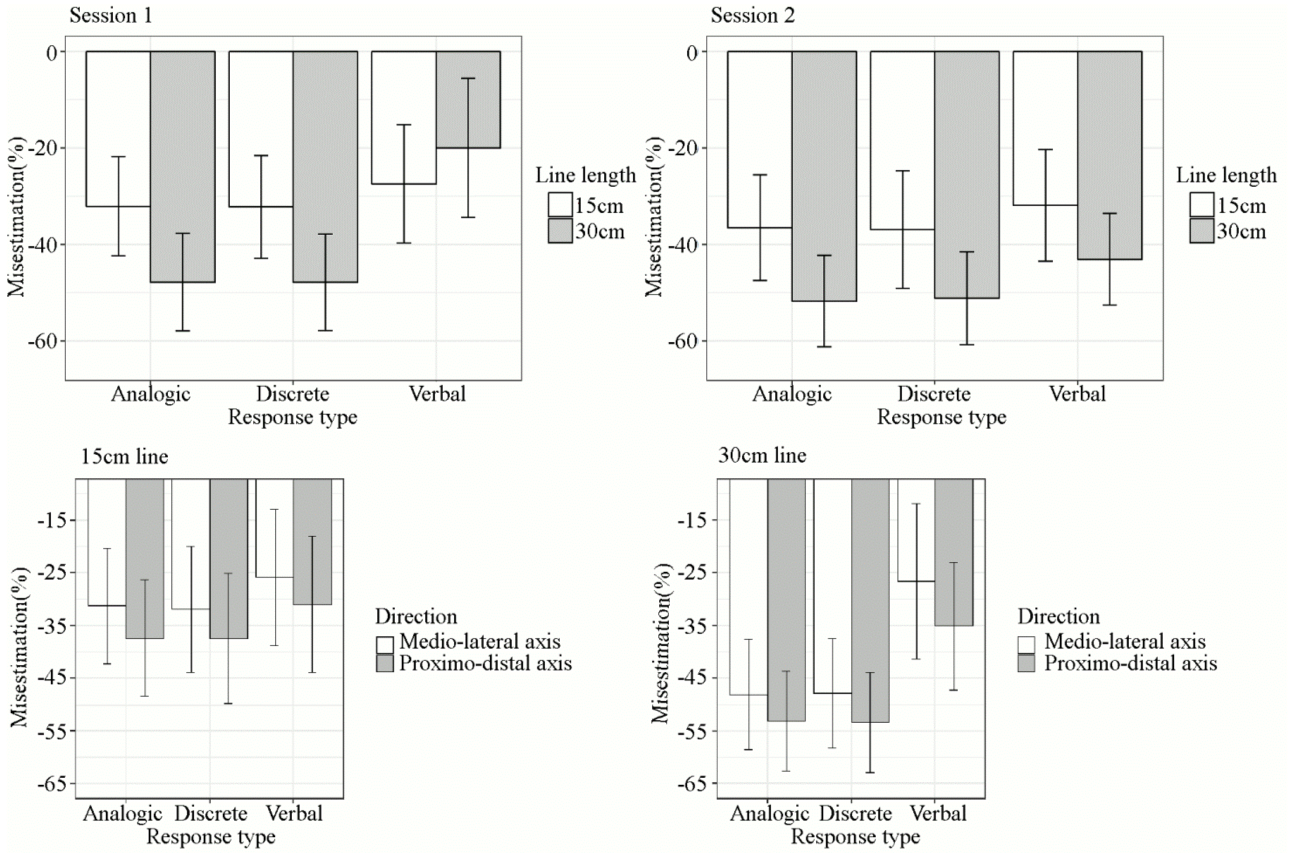

Figure 7. **Upper panel:** best-fitting model resulted from the Linear Mixed Model (LMM) selection with the misestimation as the dependent variable. The complete model included Session, Response and Line length. The figure shows the percentage of misestimation in each response conditions: Analogic, Discrete, and Verbal. The white columns represent the 15cm line condition, while the grey columns stand for the 30cm line condition. The more negative are the misestimation values, the higher is the underestimation of the leg length. **Lower panel:** difference of misestimation between proximo-distal (grey columns) and medio-lateral axis (white columns). Each column represents a condition: Analogic-15cm, Discrete-15cm, and Verbal-15cm (on the left), Analogic-30cm, Discrete-30cm, and Verbal-30cm line (on the right). The more negative are the misestimation values, the higher is the underestimation of the distances on the axis. No matter the best fitting model emerged, we found a greater reduction in proximo-distal distances rather than in the medio-lateral ones. This effect was significant in all conditions except for the discrete 15cm line, which we reported here for completeness. Error bars represent the 95% Confidence Intervals.

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Correlation analyses. The comparison between the two indeces (i.e. Procrustes Distance and Misestimation) revealed anecdotal to moderate evidences in favour to the null hypothesis, suggesting the global shape dissimilarity and the direction bias convey different information.

		Pd_analogic	**Pd_discrete**	**Pd_verbal**	**Pd_15cm**	**Pd_30cm**
Misest_analogic	Pearson's r	0,06	-0,14	-0,37	-0,17	-0,14
	BF_{10}	3,81	3,26	0,92	2,92	3,21
Misest_discrete	Pearson's r	0,05	-0,11	-0,31	-0,14	-0,12
	BF_{10}	3,84	3,45	1,42	3,19	3,45
Misest_verbal	Pearson's r	0,29	0,14	0,04	0,27	-0,06
	BF_{10}	1,61	3,25	3,90	1,82	3,81
Misest_15cm	Pearson's r	0,17	0,01	-0,10	-0,03	0,07
	BF_{10}	2,93	3,95	3,57	3,90	3,76
Misest_30cm	Pearson's r	0,09	-0,07	-0,28	0,03	-0,26
	BF_{10}	3,61	3,77	1,69	3,92	1,92

***Table 2*. Bayesian correlations.** The table shows the Bayesian correlations between the Procrustes Distance and the Misestimation in each the response modality (averaging across 15cm and 30cm lines) and each line length (averaging across the type of response); “Pd” indicates the Procrustes Distance, “Misest” indicates the Misestimation.

3.5. CONCLUSION

We used a modified version of the tactile task proposed by Longo (Longo & Golubova, 2017; Longo & Haggard, 2012a; Longo et al., 2015), in order to test body distance perception of the leg, evaluating the reliability of the method, if it is replicable and how much it is resistant to potential cognitive confounds, thus providing support for its initial scope of being a method to measure body metric perceptual representation. Additionally, we calculated both the shape dissimilarity index (i.e. the Procrustes Distance) and the directional bias (i.e. the misestimation score) thus providing a solid methodological validation to both the approaches of collecting the estimates and the way to analyse the biases. We evaluated the possible influences of different kind of response modalities that have been used in previous studies, such as imaginary verbal estimates and perceptive recalibration (Longo & Haggard, 2011; Longo et al., 2015; Longo & Morcom, 2016; Stone et al., 2018). Since perceptive recalibration might be limited by non-reproducible distances, we provided a visual reference (i.e. a line) modifying its length and the scale used. We questioned whether scaling the real distance by means of a proportional reproduction would be as successful as providing the reproduction of the physical length and if it is better to employ an analogical or discrete line with perceptive cues.

Bayesian one sample t-test showed that Procrustes Distances significantly differed from zero, no matter the response method. These results strongly support the idea that humans have a distorted map of the body, where they perceive tactile events (Longo et al., 2015; Longo & Morcom, 2016; Stone et al., 2018) which is resistant to contextual experimental effects. Notably, previous studies have found a stretch along the medio-lateral (transversal) axis, and an equivalent compression of the proximo-distal (longitudinal) one (Longo & Haggard, 2011; Longo et al., 2015; Longo & Morcom, 2016; Stone et al.,

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2018). We also checked for the presence of this systematic bias. Results showed that there was a general underestimation of the tactile distances; moreover, this distortion was higher on the proximo-distal axis than on the medio-lateral one. Regardless of the response method, subjects perceived a general reduction of the leg sizes, and, in particular, a contraction of the leg length, in line with the literature (Longo & Haggard, 2011; Longo et al., 2015; Longo & Morcom, 2016; Stone et al., 2018).

As regards to the response modality, we compared verbal and perceptive responses, supposing that the former could be based on the metric size knowledge necessary to provide an imaginary estimation, while the latter could be mediated by perceptual recalibration thus influenced by visuo-tactile integration. Moreover, we modulated the size of the line used to answer, and its scale (continuous or discrete). We assessed the influence of the response modality on both shape and distance perception through the Procrustes Distances and the percentage of misestimation. The Bayesian Repeated Measure ANOVA on the Procrustes Distance showed that the best fitting model was the null one, suggesting that the global shape of the perceptive grid is independent from the response type and it is a replicable methodology. Nevertheless, considering the directional bias, the LMM three-way ANOVA revealed a significant interaction effect between Session, Response modality and Line Length. Besides the overall underestimation of distances, we found that in the first session verbal responses were the most accurate as compared to the analogic and discrete ones. It is possible that the perceptive "cue" of the line, was actually a confounding factor for distance judgments. In both perceptual conditions, we expected participants to compare the distance between the tactile stimuli with the line presented. Since it requires a more complex cognitive process, it is possible that the visual stimulus (i.e. the line) influenced subjects' estimations. In the case of the verbal response, subjects were only asked to say the number corresponding to the distance they perceived. The comparison with the line on the screen needed a subsequent cognitive transformation that could introduce some noise. The findings about the line length confirm this hypothesis. When the visual line did not correspond to the length represented, the bias was emphasized: responses provided on a 30cm line showed a greater underestimation. In this case, we introduced an additional cognitive step: the line had to be scaled to the length it represented. This result seems to relate to a well-known distance perception bias since longer distances are usually misestimated as compared to shorter distances both on the body and in space (Longo & Golubova, 2017; Longo & Morcom, 2016; Plumert, Kearney, Cremer, & Recker, 2005). In this case, it was not the distance to judge to be longer, but the reference used to answer. As regard to the scale used in the analogic and discrete conditions, we did not find any difference. This result suggests that the perceptive cues provided with the discrete line did not help participants' responses. In the second session, we found almost the same pattern except for the verbal responses given after the 30cm line, where we found a higher underestimation of distances. We have any specific

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prediction or clue about this result; we limit our observation by now considering that it might also be a simple regression toward the mean.

The bayesian correlation analysis between the Procrustes Distance and Misestimation revealed anecdotal to moderate evidences in favour to the null hypothesis, suggesting that the two indices are not related and provide different information. We propose that the two scores should be used synergistically and not as two mutually exclusive alternatives. Indeed, the Procrustes Distance and the percentage of misestimation differed in evaluating the response modalities. Even if they referred to the same task, they represent slightly different information, confirming the results of our correlation analysis. The Procrustes Distance provides a dissimilarity index between the global shape of two configurations, without discriminating the type of distortion. It considers the global shape of each grid, but it cannot distinguish between a wide and short configuration and a tall and tight one. On the contrary, the percentage of perceived misestimation compares the distance provided by the participants at each stimuli pair and the actual gap. This measure is independent by the shape and focuses on the distances between each point of the grid. Our results suggest that different response modalities do not affect the perception of the general shape of our body parts: the characteristic distortion of the grid with a greater reduction of distance estimation along the proximo-distal axis, as compared to the medio-lateral one, is maintained regardless the cognitive processes involved in the task. This is not true if we focus on directional biases: the integration between tactile inputs and visual stimuli influences estimate precision. Indeed, verbal responses were more accurate. To understand the different results, we need to distinguish between a holistic point of view, in the case of Procrustes Distances, and a more specific one, in the case of distance misestimation. It is possible that our brain preserves the perception of the general shape of our body parts, although distorted, independently by the specific demand. However, if we examine the specific distance perception, we can notice a dependence by the cognitive processes and the sensory inputs involved. Such an organization would allow maintaining coherence and continuity to our body experience.

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[2] This chapter is extracted from the paper by Tosi, G. & Romano. The longer the reference, the shorter the legs: how response modality affects body perception (under review).

4. EXPERIMENT 3. BODY ILLUSION IMPACTS ON BODY METRIC REPRESENTATION[3]

4.1. INTRODUCTION

The scope of the current study was to evaluate if the Body Illusion (FBI) presented in Experiment 1 can impact our perception of body metric representation (Longo et al., 2010). The key question is if the body metric representation can be plastically modulated by embodying mannequins of different sizes. In other words, do we perceive our bodies and tactile events on it according to the way we represent it? To investigate this question, we replicated the FBI with different body sizes accompanying the questionnaire to the Body Distance Task (BDT) presented in Experiment 2. The working hypothesis is that the FBI affects the subjective experience of embodiment, but this subjective sensation is also accompanied by a change in the perception of body metric that goes hand-in-hand with the size of the embodied avatar.

4.2. MATERIAL AND METHODS

4.2.1. Participants

24 new healthy volunteers took part in Experiment 2 (13 females; mean age = 25 ± 5.77, range 19-48; mean education = 16.13 ± 1.85, range 13-21). All participants had normal or corrected to normal vision and were naive to the purpose of the experiment. All the subjects gave their written informed consent before participating in the experiment.

The general aim of the study and the procedure were explained to participants before collecting the informed consent. Participants were informed that the experiment was aimed to study body perception and that they would undergo two experimental sessions.

4.2.2. Procedure

The experiment consisted of two sessions, with one week of washout in between. In each condition we administered a BDT in order to investigate a possible distortion of the metric representation of the body, and the same questionnaire used in Experiment 1 to evaluate the embodiment of the artificial bodies.

Body Illusion

Each participant underwent the same Body Illusion conditions of Experiment 1. The set-up and the videos were the same as in Experiment 1, except that the syringe threat section of the clips was cut from the videos and no longer used. In each session, participants experienced the two orientations (anatomical, non-anatomical) in two different sizes, which were standard size and either small or big

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[3] This chapter is extracted from the paper by Tosi, G., Romano, D., Maravita, A. I am the meter. The representation of one's body size affects the perception of tactile distances on the body (in preparation)

according to the experimental session. In that way, all participants underwent a Small-size session and a Big-size session. The standard legs condition was considered as a baseline condition and repeated in both sessions as the first one. The order of the videos was counterbalanced across participant (24 possible combinations resulted), and Small-size and Big-size sessions were alternated following an ABBA order. This procedure resulted in 8 visuo-tactile stimulations for each participant: standard1-anatomical; standard1-non-anatomical; small-anatomical; small-non-anatomical; standard2-anatomical; standard2-non-anatomical; big-anatomical; big-non-anatomical. The different measures of the standard size stimulations were averaged between the different sessions, defining the final 3 (size: standard, big, small) by 2 (orientation: anatomical, non-anatomical) factorial design, replicating Experiment 1 design.

Embodiment questionnaire

We used the same questionnaire adopted for Experiment 1. Data were processed following the same steps of Experiment 1, namely the scores were ipsatized and then aggregated to obtain an illusion score averaging the items: Q1, Q2, Q3, Q4 (reversed), Q5, and Q6. The full questionnaire is reported in Appendix, Table 1.

We expected to replicate our previous results, finding significant effects of both Size and Orientation.

Body Distance Task Procedure

The Body Distance Task proved to be effective measuring the distortion of the metric representation of the body (Experiment 2; Longo & Golubova, 2017; Longo et al., 2015; Longo & Morcom, 2016). The BDT was administered following the same procedure than in Experiment 2. A 3x3 grid of points (see Figure 5, left panel) was applied on the upper left leg, on each trial, two locations were stimulated in sequence, with an inter-stimulus interval of approximately one second. After each trial, participants verbally estimated the perceived distance between the two stimuli locations. There were 36 possible pairs of the nine stimuli locations and two orders of presentation for each pair. Differently from Experiment 2, we administered the two different orders of presentation in two subsequent blocks (Block 1: AB order, Block 2: BA order) so that we could control for the potential effect of temporal distance from the embodiment procedure. Indeed, the administration of the entire BDT takes about 10 minutes, and it is not known if the embodiment effect can last for that long after the induction phase. By doing so, we may control for a temporal fading effect of the FBI as well adding the factor block to the analysis.

BDT – Global shape dissimilarity

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[3] This chapter is extracted from the paper by Tosi, G., Romano, D., Maravita, A. I am the meter. The representation of one's body size affects the perception of tactile distances on the body (in preparation)

We calculated the Procrustes Distances for each condition in each order of points pair (Block: AB order vs BA order). Procrustes distances have been log transformed to improve the fit with normal distribution for the inferential statistic.

BDT – Misestimation

We also calculated the percentage of perceived misestimation, considering again the direction of the tactile stimuli (medio-lateral axis/proximo-distal axis) and their distance (near-5cm/far-10cm). We used this additional index to examine subjects' misestimations of the fake leg' sizes (small/standard/big) during the BDT.

4.3. ANALYSIS

We analysed data with R 3.4.2 (R Development Core Team 2008), Jamovi 0.9.1.10 (jamovi project, 2018) and JASP 0.8.4 (Jasp Team, 2017). More specifically, to run MDS we used the packages *stats* (function *cmdscale*), Procrustes Distance have been calculated with the package *vegan* (function *procrustes*). Misestimation percentage have been calculated with ad hoc formula in R.

Embodiment questionnaire

We ran a within-subjects 3(Size) * 2(Orientation) repeated measure ANOVA. Significant effects have been interpreted inspecting 95% Confidence Intervals.

BDT – Global shape dissimilarity

Procrustes Distance ranges between 0 (i.e., the two configurations have the same shape), and 1 (i.e., the two configurations do not share spatial structure at all). We first analysed the Procrustes Distances by checking for significant differences from zero, to assess if there is any distortion in the perceived metric of the legs. To do so, we run a series of independent one-sample t-tests on the Procrustes Distances of each condition. Then, we conducted a within-subjects 3(Size) * 2(Orientation) * 2(Block) repeated measure ANOVA using as dependent variable the Procrustes distances, in order to evaluate if the FBI and/or the different body sizes modulates the eventual distortion of the BDT.

BDT – Misestimation

We run a Linear Mixed Model (LMM) two-way ANOVA with the misestimation as the dependent variable. Fixed effect factors were Direction (medio-lateral axis/proximo-distal axis) and Distance (near/far) as within-subject factors. We set participants as a random effect variable. Significant effects have been interpreted inspecting 95% Confidence Intervals.

4.4. RESULTS

Embodiment questionnaire

The 3(Size) * 2(Orientation) repeated measure ANOVA resulted in significant main effects of Size ($F(2,46)= 21.89$, $p\leq .001$, $\eta^2= .48$) and Orientation ($F(1,23)= 9.78$, $p\leq .05$, $\eta^2= .30$) replicating the

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[3] This chapter is extracted from the paper by Tosi, G., Romano, D., Maravita, A. I am the meter. The representation of one's body size affects the perception of tactile distances on the body (in preparation)

results of the Experiment 1. Once again, standard legs (CI: 0.16; 0.46) and big legs (CI: -0.02;0.42) presented in an anatomical orientation induced a stronger embodiment than small size legs (anatomical (CI: -0.42; -0.03), non-anatomical (CI: -0.66; -0.26)), as shown in Figure 8.

The results obtained from all the factors of the questionnaire are reported in Table 8 (see Appendix).

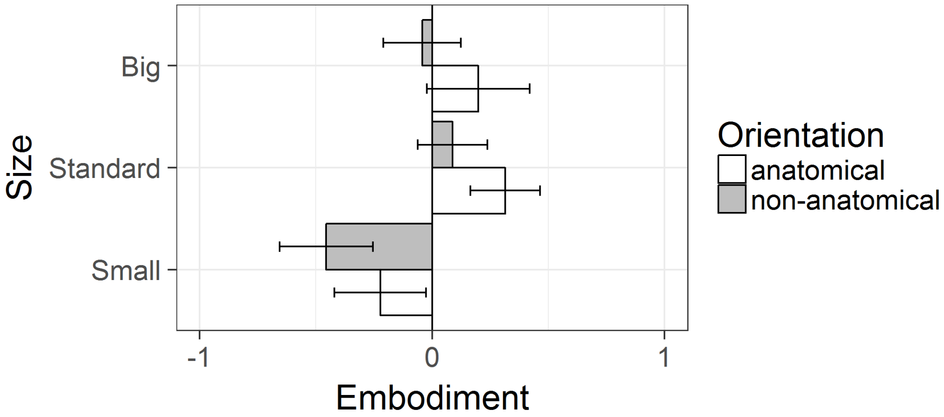

Figure 8. **Results of the rmANOVA on the averaged ipsatized answers to embodiment statements.** Grey and white columns display Non-anatomical and Anatomical conditions respectively. Error bars display confidence interval limits.

BDT – Global shape dissimilarity

The one-sample t-tests were significant for all the conditions, in both blocks (see Table 3). These results suggested that the perceived grid significantly differed from the actual grid of the targets in all conditions (Figure 9).

Condition	**df**	**t**	**p**	**d**
Small-anatomical (block 1)	23	-16.03	≤ .001	3.27
Small-anatomical (block 2)	23	-10.33	≤ .001	2.11
Small-non-anatomical (block 1)	23	-11.14	≤ .001	2.28
Small-non-anatomical (block 2)	23	-9.93	≤ .001	2.03
Standard-anatomical (block 1)	23	-26.15	≤ .001	5.34
Standard-anatomical (block 2)	23	-9.93	≤ .001	2.03
Standard-non-anatomical (block 1)	23	-19.10	≤ .001	3.90
Standard-non-anatomical (block 2)	23	-16.25	≤ .001	3.32
Big-anatomical (block 1)	23	-18.85	≤ .001	3.85
Big-anatomical (block 2)	23	-16.77	≤ .001	3.43
Big-non-anatomical (block 1)	23	-11.72	≤ .001	2.39
Big-non-anatomical (block 2)	23	-11.97	≤ .001	2.44

Table 3. **Results of the independent one sample t-tests on the Procrustes Distances.** The results suggested that the perceived grid significantly differed from the actual grid of targets in all conditions

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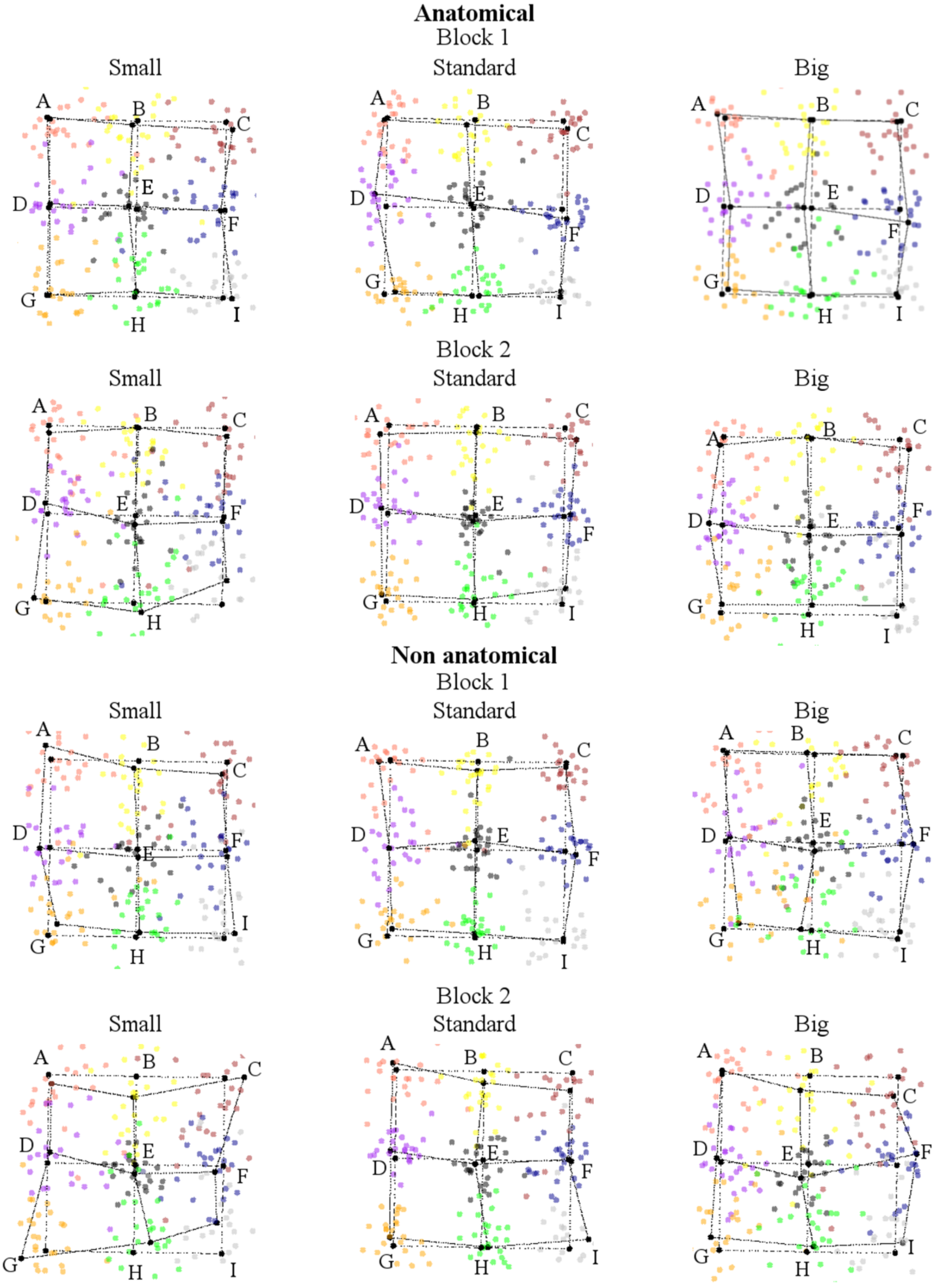

Figure 9. **Results of the Multidimensional Scaling for each condition.** The black grid represents the mean of the subjects' perceptive responses compared with the actual grid (in red). We characterized with different colours the perceived location of each point by each participant.

The 3(Size) * 2(Orientation) * 2(Block) repeated measure ANOVA resulted in a significant main effect of Size (F(2,46)= 21.45, p≤ .001, η^2= .18). Procrustes Distances were closer to zero with the Standard legs (CI: 0.24; 0.32) than with the Small (CI: 0.35; 0.49) and Big ones (CI: 0.33; 0.45)

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suggesting for a lower distortion during the conditions in which the fake legs held the same size as the participants' ones. We also found a significant main effect of Orientation (F(1,23)= 7.20, p≤ .05, η^2= .01) with Procrustes Distances closer to zero in the Anatomical condition (CI: 0.30; 0.39), than in the Non-anatomical one (CI: 0.32; 0.44). This result implies that when subjects saw the fake legs from a non anatomical point of view, their perceptive grids were more distorted than during the anatomical condition. Crucially, we found a significant interaction between Size and Orientation (F(2,46)= 3.31, p≤ .05, η^2= .01), as shonw in Figure 10, left panel. We found similar distortions between the Anatomical and Non-anatomical conditions for the Standard (anatomical (CI: 0.25; 0.32); non-anatomical (CI: 0.25; 0.33)) and the Small legs (anatomical (CI: 0.35; 0.47); non-anatomical (CI: 0.35; 0.49)). On the contrary, in the Big legs condition emerged a difference between anatomical (CI: 0.31; 0.39) and non-anatomical viewpoint (CI: 0.37; 0.49). The right panel of Figure 10 shows the Procrustes Distances as a function of stretch for both subjective and actual leg maps in these two conditions. The stretch that minimized the Procrustes distance for the bigger legs (dotted line) was higher than for the standard ones (dashed line), suggesting a greater stretch in the proximo-distal leg axis after the videos with the longer legs compared to the standard ones.

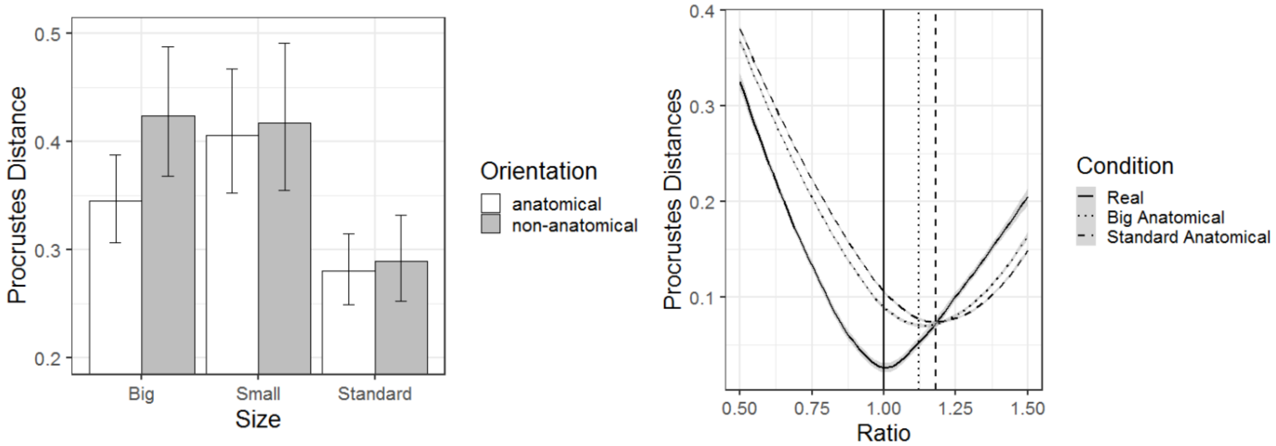

Figure 10. **Left panel: two-way interaction between Size and Orientation.** Grey and white columns display the mean Procrustes Distances of the Non-anatomical and the Anatomical conditions respectively; error bars display confidence interval limits. **Right panel: mean Procrustes distance between actual (solid line) and perceptual (dotted and dashed lines) maps and simulated grids stretched by different amounts.** A stretch of 1 indicates a square grid; values greater than 1 indicate a higher underestimation in the proximo-distal axis, while values less than 1 indicate a higher underestimation in the medio-lateral axis. The vertical lines indicate the mean of the best-fitting stretches for subjective maps (dotted for the standard legs and dashed for the bigger ones) and actual maps (solid line). The stretch that minimized the Procrustes distance for the bigger legs (dotted line) was bigger than for the standard ones (dashed line), indicating a greater stretch in the proximo-distal leg axis after the videos with the longer legs compared to the standard ones.

BDT – Misestimation

The 2 (Direction) * 2 (Distance) LMM ANOVA on the misestimation in Block 1 revealed the following results. In the Standard-anatomical condition, we found significant main effects of both Direction (F(1,405)= 6.00, p≤ .05) and Distance (F(1,405)= 9.15, p≤ .05). The perceived distances

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between points running along the proximo-distal axis were more underestimated (CI: -45.5; -25.1) than along the medio-lateral axis (CI: -41.3; -21). Moreover, we found a higher underestimation for long distances (CI: -46.0; -25.5) than for short ones (CI: -40.7; -20.6). On the contrary, in the other conditions we only found a significant main effect of Distance (Standard-non-anatomical (F(1,405)= 55.42, p≤ .001); Big-anatomical (F(1,405)= 55.11, p≤ .001); Big-non-anatomical (F(1,405)= 31.02, p≤ .001)); Small-anatomical (F(1,405)= 39.24, p≤ .001); Small-non-anatomical (F(1,405)= 37.49, p≤ .001)). The latter result confirms higher underestimation for long distances (mean CI: -50.86; -26.42) than for short ones (mean CI: -37.58; -13.60). Therefore, in the anatomical condition we found a contraction of the proximo-distal axis only for the standard legs, but not for the bigger ones. This distortion is also confirmed in the right panel of Figure 10.

Looking at the Block 2, we found significant main effects of both Direction and Distance in all the conditions: Standard-anatomical Direction (F(1,405)= 14.53, p≤ .001); Standard-anatomical Distance (F(1,405)= 35.89, p≤ .001); Standard-non-anatomical Direction (F(1,405)= 21.01, p≤ .001); Standard-non-anatomical Distance (F(1,405)= 35.64, p≤ .001); Big-anatomical Direction (F(1,405)= 16.46, p≤ .001); Big-anatomical Distance (F(1,405)= 35.59, p≤ .001); Big-non-anatomical Direction (F(1,405)= 16.73, p≤ .001); Big-non-anatomical Distance (F(1,405)= 46.65, p≤ .001); Small-anatomical Direction (F(1,405)= 7.98, p≤ .05); Small-anatomical Distance (F(1,405)= 27.18, p≤ .001); Small-non-anatomical Direction (F(1,405)= 24.33, p≤ .001); Small-non-anatomical Distance (F(1,405)= 33.70, p≤ .001). The results went in the same direction of the first block, with higher underestimations for long distances (mean CI: -55.52; -32.75) than for short ones (mean CI: -44.55; -22.23) and along the proximo-distal axis (mean CI: -54.65; -31.08) compared to the medio-lateral one (mean CI: -46.42; -23.83). Moreover, we found a significan interaction between Direction and Distance in the Standard-anatomical condition (F(1,405)= 7.17, p≤ .05).

4.5. CONCLUSION

The present experiment confirmed that the FBI induces a robust perceptual delusion of embodying the image of alien body segments of equal or bigger size than the owner's body part. Indeed, our participants experienced strong embodiment with both the standard and the big-sized legs when these were presented from an anatomical point of view, in full agreement to the results of Experiment 1. Here we combined the FBI with the BDT, in order to find out if the illusion related to the body size could also affect the perception of body metric.

We processed tactile distance estimations with the Multidimensional Scaling, in order to generate a perceptive configuration of the grid to be compared with the actual one. The Procrustes Distances suggested that subjects' perceptual maps significantly differed from the real grid in all

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conditions. These results are in line with the results of Experiment 2 and with previous findings on both the hand (Longo et al., 2015; Longo & Morcom, 2016) and the leg (Stone et al., 2018). Perceived legs' sizes are distorted as compared to their physical dimensions, suggesting that the body model underlying tactile and proprioceptive information about the body is distorted (Longo et al., 2015; Longo & Morcom, 2016).

Interestingly, the shape of the grids was more distorted during the non-anatomical (non-embodied) condition than during the anatomical one suggesting a key role of embodiment in body metric processing. Moreover, Procrustes Distances were closer to zero with the standard legs than with the small and big ones suggesting for a more distorted perception during the conditions in which the fake legs held a different size of legs as compared to the the participants' ones. Since we know that proprioceptive information about the body is distorted, these results suggested that any interference with the visual input from the body (i.e. a different size of the legs or a a view-point 45° clock-wise rotated) could potentially increase this distortion, affecting our body perception.

Crucially, we found a two-way interaction between Size and Orientation: in the Big legs condition emerged a difference between the anatomical and the non-anatomical viewpoint.

The vision of one's body is known to alter the perception of tactile (Kennett, Taylor-Clarke, & Haggard, 2001; Longo, Cardozo, & Haggard, 2008; Press, Taylor-Clarke, Kennett, et al., 2004) and painful (Longo, Betti, Aglioti, & Haggard, 2009; Romano & Maravita, 2014) stimuli. We propose that when the fake body is embodied, then it is processed as one's body, which views improve the processing of somatosensory stimuli and thus possibly reduced the distorsion effect. Participants perceived a less distorted grid when they embodied the longer legs than when they did not (i.e. in the control condition).

Differently from the big legs conditions, the Procrustes Distances showed a similar distortion between the Anatomical and the Non-anatomical orientations either for the standard and the small legs, however this happened with a much different general effect of distortion determined by the size. From the embodiment questionnaire results, we know that the small legs did not induce any embodiment effect, coherently this turn to a larger distortion than the other conditions and a comparable one to each other.

The situation is different for the standard size legs. Indeed, following the above mentioned hypothesis, the non-anatomical legs should result in a distorted grid, because they are less embodied than the anatomical. However, it is important to note, that the embodiment questionnaire showed that the non-anatomical standard legs have an ipsatised score bigger than 0, and importantly, larger than the non-anatomical big legs and the two pairs of small legs. Possibly, in case of proper size and congruent visuo-tactile stimulation, even if there is a misalignement between vision and proprioception, it is

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possible to induce embodiment to a certain degree. This minum embodiment is reflected in the questionnaire, but it is not limited to it. Indeed, the grid distortion is minimised in the non-anatomical-legs as if the participants were looking at their legs.

These findings suggests that the vision of one's body can impact the metric representation of it, and crucially to our purposes, this can be modulated by the seen size of the to-be-embodied body. This hypothesis is confirmed by the misestimation results that revealed in the first block an underestimation of distances running along the proximo-distal axis as compared to the medio-lateral axis only for the anatomical standard legs but not for the bigger one. After embodying the bigger legs, our participants perceived their limbs longer as compared with the other illusory conditions.

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[3] This chapter is extracted from the paper by Tosi, G., Romano, D., Maravita, A. I am the meter. The representation of one's body size affects the perception of tactile distances on the body (in preparation)

5. EXPERIMENT 4. THE EFFECTS OF MIRROR BOX TRAINING IN THE BODY REPRESENTATION OF HEMIPLEGIC STROKE PATIENTS[4]

5.1. INTRODUCTION

Since we confirmed that in healthy subjects the metric representation of the body can be modulated by emboding bodies holding different sizes, we addressed a similar question in patients with hemiplegia.

In the present study, we first assessed whether hemiparetic post-stroke patients show any proximal bias of the forearm metric perception, likely due to non-use. Critically, we investigated if this bias may change after a Mirror Box (MB) training session, compared to a control training without the mirror. In addition, we aimed at qualifying any effects of the MB relatively to individual clinical features, such as lesion side and the duration of the disorder. We chose to evaluate metric representation of the distal portion of the paretic arm (i.e., from the elbow to the tip of the middle finger), which is typically the most affected part as compared to more proximal segment (Hallett, 2001).

5.2. MATERIALS AND METHODS

5.2.1. Participants

A continuous series of 53 participants were selected to take part in the study (15 females, 38 male). Participants were inpatients admitted to the Rehabilitation Unit of Bassini Hospital, Cinisello Balsamo (Mi), or Sant'Antonio Abate Hospital, Somma Lombardo (Va), following post-stroke, acquired motor impairment. Exclusion criteria included; (i) worsening of health condition between the two experimental sessions, (ii) cerebellar lesions, and (iii) multiple brain accidents. Due to the exclusion criteria, the final sample included in the study was composed by 45 patients (15 females; mean age= 66.36±11.81, range 38-87; mean education= 9.42±4.08, range 3-18). 25 patients were in the subacute phase (acute stroke event occurred within the previous 3 months) and 20 patients presented with a chronic impairment (Yavuzer et al., 2008). Concerning the lesion side, there were 22 left brain damage (LBD) and 23 right brain damage (RBD) patients. Essential biographic and clinical characteristics of participants are presented in Table 4.

Patient	Age	Sex	School Age	Location/Lesion Side	Plegia	Chronicity
P1	68	M	8	lenticulo-capsular/L	right	no
P2	42	M	13	nucleo-capsular/L	right	no
P3	85	F	8	lenticulo-capsular/R	left	yes
P4	71	F	13	F-T-P-insular/R	left	no
P5	87	F	8	frontal/L	right	no

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[4] This chapter is based on the paper by Tosi, G., Romano, D., & Maravita, A. (2018). Mirror box training in hemiplegic stroke patients affects body representation. *Frontiers in human neuroscience*, *11*, 617.

P6	63	F	5	F-P-ganglia-internal capsule/L	right	yes
P7	75	M	5	F-T-P/R	left	no
P8	74	M	11	frontal/R	left	no
P9	76	M	12	F-T-P/R	left	no
P10	61	F	5	nucleo-capsular/L	right	yes
P11	49	F	13	nucleo-capsular/L	right	yes
P12	75	M	13	O-P/R	left	yes
P13	63	F	5	lenticulo-capsular/R	left	yes
P14	63	M	5	middle cerebral artery/R	left	no
P15	69	F	8	F-P/R	left	no
P16	64	M	7	R	left	yes
P17	86	M	5	lenticulo-capsular/R	left	no
P18	60	M	11	F/S	right	no
P19	73	M	8	capsulo-lenticular/L	right	no
P20	50	M	10	T-P/L	right	yes
P21	75	M	5	T-P-capsulo-thalamic/R	left	no
P22	77	F	3	parietal/L	right	yes
P23	71	M	5	caudate n-corona radiata/L	right	no
P24	70	M	5	temporal/L	right	yes
P25	69	M	13	middle cerebral artery/R	left	yes
P26	72	M	6	talamo-capsular/L	right	yes
P27	76	M	5	middle cerebral artery/R	left	no
P28	63	M	13	parietal/L	right	yes
P29	60	M	9	L	right	yes
P30	54	M	16	pericallosal artery/R	left	no
P31	58	M	13	internal capsule/R	left	no
P32	49	M	5	internal capsule/L	right	no
P33	82	M	10	precentral gyrus/R	left	no
P34	77	F	8	T-P/R	left	no
P35	73	F	5	corona radiata/L	right	no
P36	62	M	8	middle cerebral artery/R	left	yes
P37	62	F	17	T-P/R	left	yes
P38	63	M	13	middle cerebral artery/L	right	no
P39	75	M	8	hemorrage/R	left	yes
P40	67	F	13	F-T-P/R	left	no
P41	80	M	11	insula hemorrage/R	left	no
P42	41	M	18	middle cerebral artery/L	right	yes
P43	67	M	8	hemorrage/L	right	yes
P44	51	F	16	L	right	yes
P45	38	F	18	L	right	yes

Table 4. **Demographic characteristic of the sample.** Sex: M= male, F= female, Location/Lesion side: F= frontal lobe, P= parietal lobe, O= occipital lobe, T= temporal lobe; L= left hemisphere, R= right hemisphere; Chronicity: yes= stroke event occurred more than three months before, no= stroke event occurred within the previous 3 months.

5.2.2. Procedure

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[4] This chapter is based on the paper by Tosi, G., Romano, D., & Maravita, A. (2018). Mirror box training in hemiplegic stroke patients affects body representation. *Frontiers in human neuroscience*, *11*, 617.

Patients underwent two experimental sessions, separated by one wash out week (Figure 11, panel A). At the beginning of the first session all patients underwent a standard neurological examination (Bisiach, et al., 1983), including strength, visual field, proprioception, tactile perception and personal neglect. In each session participants were asked to perform a forearm bisection task before and after a motor training session. Two different motor training conditions were tested, either using the MB or not. Training sessions were counterbalanced across participants (Mirror/No-Mirror): 23 patients used the MB in the first session, while the other 22 started with the training without the MB.

This study was carried out in accordance with the recommendations of the Ethic Committee "Commissione per la Valutazione della Ricerca, Dipartimento di Psicologia" of the University of Milano-Bicocca All subjects gave informed consent in accordance with the Declaration of Helsinki (World Medical Organization, 1996). The protocol was approved by the Ethic Committee "Commissione per la Valutazione della Ricerca, Dipartimento di Psicologia" of the University of Milano-Bicocca.

Neuropsychological screening

All patients underwent a standard neurological examination (Bisiach, et al., 1983), including strength, visual field, proprioception, tactile perception and personal neglect, following the procedure described by Bisiach and colleagues (Bisiach, et al., 1986). Each specific test and scoring are detailed below.

Strength: participants had to extend both their arms in front of them, keeping the palm up, with eyes closed. The scores were: 0= patient keeps the position at least for 30 seconds; 1= patient shows finger abduction, main creuse (i.e. thumb abduction), Gierlich (i.e. hand pronation), Barrè (i.e. downward drift) without touching the table within 15 seconds; 2= patient shows Barrè sign, touching the table within 15 seconds; 3= the limb touched the table within 5 seconds. Scores between 0 and 1 are considered as mild impairment (subjects keep the position at least for 15 seconds), scores between 2 and 3 are considered as strong impairment.

Visual field examination: 20 randomized visual stimuli (4 ipsilateral to the lesion side, 6 contralateral, 10 bilateral) were administered to the patient's superior visual field. If subject got 7 or less contralateral stimuli, then 12 ipsilateral and 10 contralateral randomized stimuli were presented. The scores were: 0= patient gets 8/10 bilateral stimuli with 10/14 ipsilateral; 1= patient gets ≤7 bilateral stimuli with 10/14 ipsilateral; 2= patient gets 4/7 unilateral stimuli with 0/12 ipsilateral; 3= patient gets 0/3 unilateral stimuli with 10/12 ipsilateral.

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Tactile perception: 20 randomized tactile stimuli (4 ipsilateral to the lesion side, 6 contralateral, 10 bilateral) were administered on the patient's hands, with lack of vision. If subject got 7 or less contralateral stimuli, then 12 ipsilateral and 10 contralateral randomized stimuli were presented. The scoring was: 0= patient gets 8/10 bilateral stimuli with 10/14 ipsilateral; 1= patient gets ≤7 bilateral stimuli with 10/14 ipsilateral; 2= patient gets 4/7 unilateral stimuli with 0/12 ipsilateral; 3= patient gets 0/3 unilateral stimuli with 10/12 ipsilateral (strong impairment). Scores between 0 and 2 are considered as mild impairment (subjects get some contralateral stimuli).

Proprioception: the examiner moves the patient's impaired hand and the patient has to move the other arm in order to reach the same posture, keeping his eyes closed. The scores were: 0= correctly done (preserved proprioception); 1= the patient perceives the movement but can't reach the other hand's final position; 2= the patient doesn't perceive the movement. Scores between 1 and 2 are considered as strong impairment (subjects cannot recognize the impaired hand position without vision).

Personal neglect: patient, keeps forearms stretched radially on a desk and tries to reach for the impaired hand with the intact one, keeping eyes closed. The same task was repeated with the experimenter's hand between the patient's ones, in order to test for eventual mistakes in reaching behavior (misattribution). The scores were: absent= patient correctly reaches his/her hand in both conditions; present= patient can't reach his/her hand at least in one condition.

Forearm bisection

Participants sat on chair, with their forearms placed radially on a table, and they were asked to point at the midpoint of their impaired arm, considering the tip of the middle finger and the elbow (olecranon) as the radial and proximal extremes. Patients were asked to indicate the midpoint with a ballistic movement, with eyes closed. On each trial, a flexible ruler was used to measure the patient's performance, setting the 0cm point in correspondence of the tip of the middle finger. 15 trials of bisection pointing were recorded. Before the task the arm length was measured.

There was no time constraint for the bisection task, but corrections were not allowed. Participants performed a total of 30 trials (15 before and 15 after each training) in each session, for a total of 60 trials per participants.

For each participant a percentage score was calculated for each forearm bisection trial using the following formula: [(p/arm length)*100], where p indicates the subjective midpoint. In this formula, a value of 0% corresponds to the tip of the middle finger, 100% corresponds to the elbow. A value higher than 50% indicates a deviation of the subjective midpoint towards the elbow (i.e. proximal deviation), while a value lower than 50% indicates a deviation towards the hand (i.e. distal deviation)

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[4] This chapter is based on the paper by Tosi, G., Romano, D., & Maravita, A. (2018). Mirror box training in hemiplegic stroke patients affects body representation. *Frontiers in human neuroscience*, *11*, 617.

(Garbarini, Fossataro, Berti, Gindri, Romano, Pia, della Gatta, et al., 2015; Daniele Romano, Uberti, Caggiano, Cocchini, & Maravita, 2018; Sposito, Bolognini, Vallar, Posteraro, & Maravita, 2010; Sposito et al., 2012). For the analysis we considered the difference between pre- and post-training bisections (pre-training minus post-training). Positive values of this shift indicate a distal deviation, i.e. a drift of the subjective midpoint towards the hand, while negative values indicate a proximal deviation, i.e. towards the elbow.

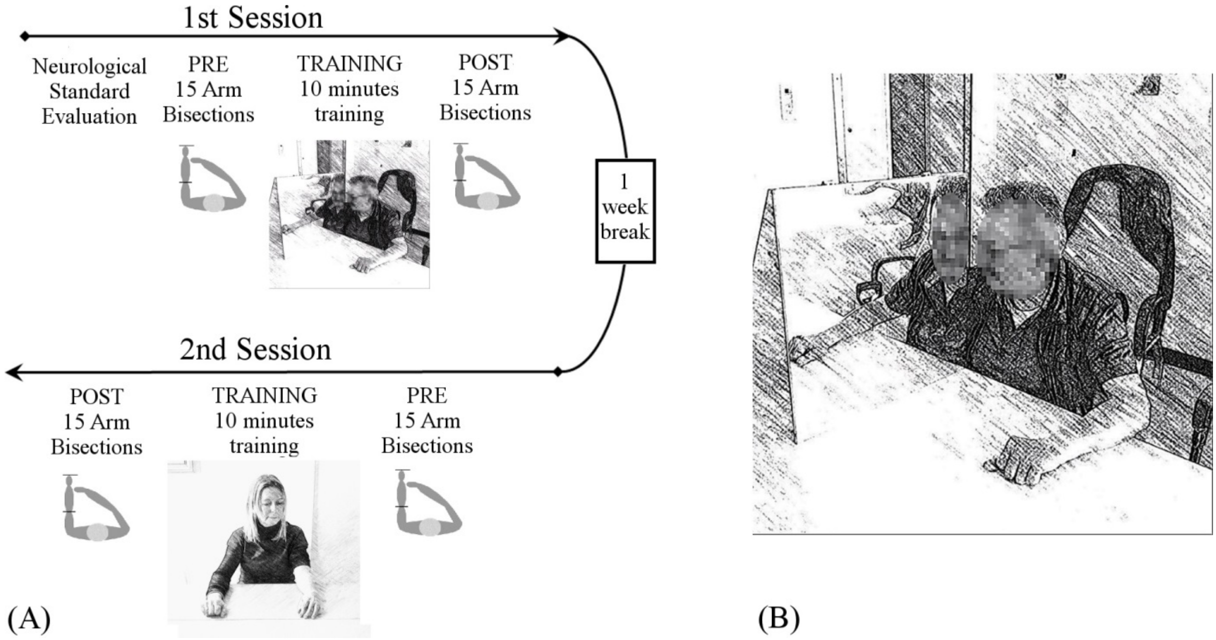

Figure 11. **Experimental procedure (Panel A).** All patients underwent a standard neurological examination, including strength, visual field, proprioception, tactile perception and personal neglect. Then patients underwent two experimental sessions, separated by one week, in which 2 different motor trainings were tested, either using the MB or not. In each session participants performed two forearm bisection tests, one before and one after each motor training. The training lasted 10 minutes and it consisted of simple hands movements that patients were invited to try and perform with both hands simultaneously, with and without the MB. Training sessions order was counterbalanced across participants. **Experimental set-up of the Mirror Box training (Panel B).** The MB was placed with the reflective surface parallel to the participant's midsagittal plane. The impaired limb was placed inside the MB and was hidden from view, while the contralateral limb was placed in front of the mirror in such a way that its reflection exactly matched the felt position of the hand inside the MB.

Motor training

The training, lasting 10 minutes, consisted of simple hands movements (e.g., opening/closing their hands, or whole hand tapping, or single finger tapping; see Table 5) that patients were invited to try and perform with both hands simultaneously, no matter the motor abilities of the affected hand (Altschuler et al., 1999; Ramachandran & Altschuler, 2009).

Hand movements	**Duration**
Opening/closing the hand	2 min
Whole hand tapping	2 min
Single finger tapping	2 min

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Whole hand lateral rotation	2 min
Tapping of palm and back of the hand alternatively	2 min

Table 5. **Hand movement requested during the motor training.** The motor training lasted10 minutes and was administered with and without the Mirror Box in two different sessions.

We chose to train the hand only, and not the whole arm, because motor impairment typically affects more the distal than the proximal limb region, leading to a reduction of motor ability and the cortical representation of the former, with relatively retained strength of the latter (Dohle et al., 2009). Since there is a "functional competition" between body parts for cortical representation in the motor region, it is possible that the simultaneous use of the proximal and distal muscles may limit the chance of the more affected hand muscles to improve their representation (Hallett, 2001). Each patient performed the motor training with and without the MB in two different sessions (Figure 11, panel A). The MB consisted of a triangular-shaped structure with the basis and one face made of plywood (50 × 50 cm and 50 × 75 cm), while the third face was a mirrored surface (50 × 50 cm).

In the MB condition the experimental device was placed with the reflective surface alongside the participant's midsagittal plane. The impaired limb was inside the MB and hidden from view, while the contralateral limb was located in front of the mirror. Hands were placed at the same distance from both side of the mirror, in the same position. With this arrangement, participants could see the hand outside the box through its mirror reflection, that exactly matched the felt position of the hand inside the MB (Panel B of Figure 11). During the motor training, the experimenter constantly recalled participant's attention toward the mirror reflection. In the control condition patients were asked to perform the same actions, but the MB was removed and thus both hands were visible.

5.3. ANALYSIS

We run a Mixed Model Analysis as implemented in SPSS 22.0 (IBM, Chicago, Illinois), considering 90% Confidence Interval limits for exploring significant interactions. The dependent variable was bisection shift. Fixed effect factors were Condition (Mirror/no-Mirror), Lesion side (Right/Left), and Chronicity (Subacute/Chronic). Patients were considered as clustering variable.

We also conducted three supplementary analyses in order to control for any possible influences of clinical variables. The dependent variable was bisection shift. Fixed effect factors were Condition (Mirror/no-Mirror) and respectively. Strength (Mild impairment/Strong impairment), Tactile perception (Mild impairment/Strong impairment), Proprioception (Preserved/Impaired) or Neglect (Absent/Present). Patients were considered as clustering variable.

5.4. RESULTS

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The main factor Condition was significant [F(1, 1304.6)= 28.385; p<.001], showing that MB training positively affects bisection task. We found a distal deviation in the mirror condition (CI: 0.9; 3.1), while a proximal deviation resulted following the no-Mirror condition (CI: -1.3; 0.9). Moreover we found a significant interaction between condition and lesion side [F(1, 1304.6)= 4.910; p<.05]. Right brain damaged patients showed a distal shift both in the Mirror (CI: -.1; 3.1) and in the No-Mirror (CI: -1.4; 1.7) condition, even if the deviation is grater in the first condition. On the contrary for left brain damaged patients we found a distal drift only with the mirror (CI: 1.0; 4.1), while the bisection point shifts toward the shoulder in the No-Mirror condition (CI: -2.2; .9).

Crucially we found three-way significant interaction involving all the fixed effects Condition, Lesion side and Chronicity [F(1, 1304.6)= 11.128; p=.001]. In the Mirror condition a larger distal shift was observed in chronic left-brain damaged patients [CI: 1.7; 5.6] than chronic right-brain damaged patients [CI: -1.5; 3.5]. In subacute phase the average distal shift is comparable in left [CI: -.8; 3.9] and right [CI: .2; 3.9] brain damaged patients. Conversely we found a proximal shift in the No-Mirror condition in all patients (subacute left brain damaged [CI: -3.2; 1.5]; chronic left brain damaged [CI: -2.4; 1.5]; subacute right brain damaged [CI: -3.1; .6]) except for chronic right brain damaged that showed a deviation towards the hand (CI: -.9; 4.1) in this condition as well (see Figure 12).

No further significant effects emerged (all other p-values>.210).

The results of the supplementary analyses are presented in Tables 9, 10, 11 and 12 (see Appendix)

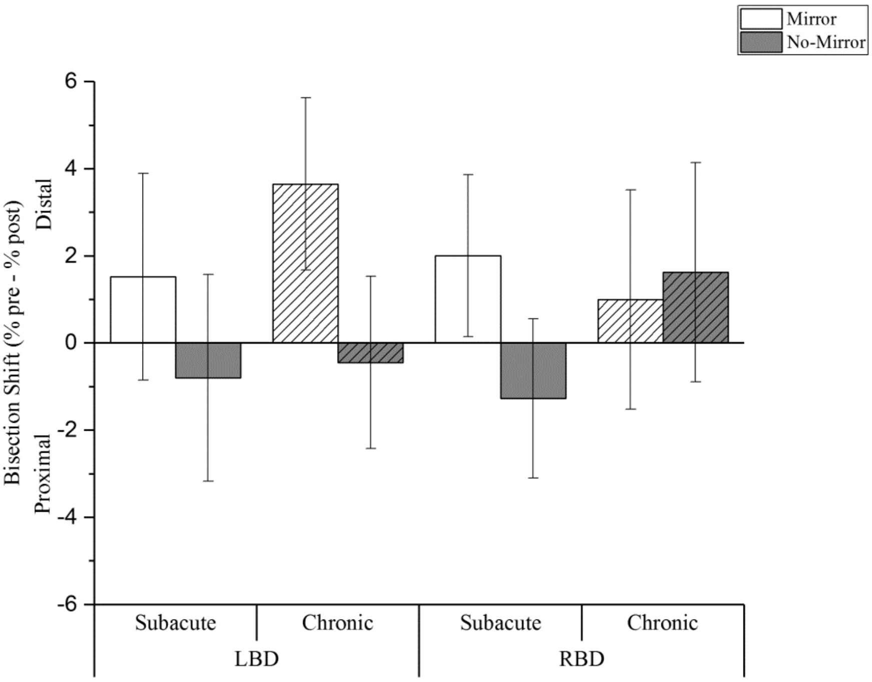

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Figure 12. **Experimental results.** Columns indicate the shift (%) of the perceived forearm midpoint calculated as a pre-training performance minus post-training performance. Positive values indicate a shift of perceived midpoint towards the hand (i.e., distal deviation), negative values indicate a shift of perceived midpoint towards the elbow (i.e., proximal deviation). Light columns show the results for the MB training condition, dark columns for the No-Mirror training condition. Full color columns show results for subacute groups, diagonal lines pattern columns represent the chronic patients' groups. Thin bars indicate Confidence Intervals set at 90% level.

5.5. CONCLUSION

Body representation is largely influenced by actions and movements (Cardinali, et al., 2009; Carruthers, 2008; Longo et al., 2010; Maravita et al., 2003; Sposito et al., 2010). Motor and biomechanical constraints critically segment our body into prototypical functional units (De Vignemont, et al., 2007) each of those, through its ability to move and to perceive a movement, can affect the global body representation. Brain damage can significantly affect movement, by disrupting central structures devoted to motor control. Moreover, the non-use of the affected limb further impinges on the motor deficit by adding what has been called "learned paralysis" (Taub et al., 1998). This additional deficit has been proposed to be grounded on the progressive reduction of the cortical representation of that underused body part representing a form of maladaptive plasticity (Dohle et al., 2009). The facilitation of motor function induced by the MB may be of potential help in improving the cortical representation of the affected body part, thus contrasting the effects of negative plasticity. This mechanism has been already proposed to be effective in the treatment of phantom limb pain with the MB as originally described by Ramachandran (Ramachandran, 1996). While MB was already proven to be effective rehabilitating motor functions (Altschuler et al., 1999; Ramachandran & Altschuler, 2009; Yavuzer et al., 2008), our experiment shows for the first time that MB also induces changes in body representation in the same kind of patients with post-stroke motor deficit.

Although the MB is a promising rehabilitative tool, its underlying mechanisms in the improvement of hemiparesis still need to be clarified. Recent experiments in neurologically unimpaired participants point to the importance of the embodiment of the image of the reflected limb in affecting sensory processing of the hidden arm (Romano, et al., 2013). As we stated before, embodiment can be defined as the attribution of some properties of an external object to one's own body (De Vignemont, 2011). As for the Body Illusion presented in Experiment 1 and 3, the MB would create a contrast between the perception of an impaired arm and the visual feedback compatible with a movement performed by that arm. In this conflicting situation, the visual capture from the reflected image would overwrite to some extent proprioceptive and somatosensory information, resulting into the embodiment of the mirror-reflected hand together with its properties of a functional limb (Romano et al., 2013). This illusory representation of the limb as a functional healthy one, would be then used to

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plan movements (Garry, et al., 2005; Holmes, et al., 2006) and process sensory input like visual (Ritchie & Carlson, 2010), proprioceptive (Romano et al., 2013) and tactile (Bultitude, et al., 2016) information. Neuroimaging results seem to corroborate this view by showing that a MB setting, analogous to the one used in the present work, in stroke patients affected by motor impairments, activates regions of the precuneus and posterior cingulate cortex, critical for body and spatial representation (Michielsen, et al., 2011).

The present work supports the idea that the MB exerts a direct effect on body representation. In particular in order to measure the metric representation of the impaired limb, we employed a forearm bisection task in which patients are asked to mentally represent the length of the to-be-bisected body part (i.e. the impaired arm in our case), and to point at its perceived midpoint. This paradigm has been used investigating the metric representation of the body in healthy participants and brain-damaged patients (Sposito et al., 2010), moreover it also proved to be sensitive to experience-induced plasticity, such as that induced by a short training with a tool (Garbarini et al., 2015; Sposito et al., 2012).

Our results showed that forearm bisection task is modulated selectively following MB training and not after a training without the MB suggesting that bilateral movements of the hand are not enough to induce a recalibration of body metric representation, ruling out a possible general effect of the intention to move.

It is worth noting that all patients showed a proximal deviation of the subjective midpoint at baseline of about 17% suggesting that the arm is implicitly represented shorter than it actually is. This is in contrast with previous experiments using a similar forearm bisection task in neurologically unimpaired participants, where the baseline deviation was about 3% toward the hand (Sposito et al., 2012). This observation go hand in hand with the hypothesized contraction of cortical representation of affected limbs, occurring after brain lesion (Dohle et al., 2009). Following MB training, the subjective midpoint shifts toward the hand, thus toward the objective midpoint, as if the arm was now perceived longer than just before the training.

This main finding suggests that even a single training session with MB can improve body representation in hemiplegic patients, showing short term effects similarly to those observed with other forms of embodiment, like those experienced following a training with a tool (Sposito et al., 2012). In line with our working hypothesis the MB may have realigned the visual feedback with the patient's intention-to-move the affected limb, promoting the embodiment of the mirrored healthy arm. This process of embodiment is also supported by the anecdotal observation that many of our patients reported the subjective experience of incorporating the mirror-reflected arm. One of our patients said, "It seems that the mirror-reflected hand is the real one", while another reported "I felt my paralyzed

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hand moving as the other one. That is crazy! It seemed alive". We suggest that the Mirror Box training compensate for the non-use of the affected limb, opposing "learned paralysis" (Taub et al., 1998).

A second important result was that chronic patients with left brain injury showed the strongest impact of MB in the body representation task, supporting the idea that these patients might be particularly suited for benefitting from the MB therapy. Chronic patients showed a larger proximal deviation of the subjective midpoint towards the elbow before the training. This is compatible with a long-lasting negative plasticity of the cortical representation of the affected arm. Notably we found that the impact of MB on body representation is also influenced by the lesion side of the stroke. Specifically, MB seems to be more effective in left brain damaged patients, where it produced a larger distal shift.

There are several, non-mutually exclusive, explanations for this finding. First, the performance of right brain damaged patients might be influenced by Unilateral Spatial Neglect (USN). USN is the failure to report, respond, or orient to novel or meaningful personal or extrapersonal stimuli presented to the side opposite a brain lesion, when this failure cannot be attributed to either sensory or motor defects, more typically occurring after right brain injury (Heilman, et al., 1993; Vallar, & Maravita, 2009). Since the mirror is placed slightly off the midsagittal plane, towards the affected side, in order to make the reflection visible, in right brain damaged patients this may fall into the possibly neglected space. Although during the motor training attention toward the mirror was constantly suggested, this may have potentially reduced the impact of the visual feedback in patients with USN, as compared to left brain-damaged patients who typically do no not show neglect. The influence of USN is typically stronger immediately after brain damage, so we have checked the presence of UNS into the medical records of our patients at the time of admission to the hospital. USN was reported in 7 right brain damaged patients, equally distributed through the subacute (4) and the chronic (3) groups, suggesting that USN cannot explain on its own the effect that we observed. An alternative hypothesis could be that the body schema is basically a sensory-motor representation of the body in space (Cardinali et al., 2009; De Vignemont, 2010), and its tight relation with spatial processing implicitly put it as a right hemisphere function (Devinsky, 2000), even if direct evidence are still lacking. It is possible that left brain damaged patients have a more spared body schema, so that they are more susceptible to an experimental manipulation that involves body schema functions. It is worth noting, however, that a previous work has failed to correlate lesion side to the effect of MB training on motor functions (Dohle et al., 2009), so that this point needs further investigations. MB therapy is actually used with different pathological conditions, like phantom limb (Ramachandran & Rogers-Ramachandran, 1996), complex regional pain syndrome (McCabe et al., 2003), post-stroke motor impairments (Altschuler et al., 1999; Dohle et al., 2009; Yavuzer et al., 2008), Anton-Babinsky syndrome (Verret & Lapresle, 1978).The idea

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that it works by restoring the brain representation of the impaired limb is helpful to tailor more precise rehabilitation protocols on each specific patient, also opening its use in novel conditions where a body representation disorder is the core of the impairment, as recently explored in the Alien Hand Syndrome (Medina et al., 2015; D Romano et al., 2013b).

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6. EXPERIMENT 5. THE RELATIONSHIP BETWEEN BODY REPRESENTATION AND INTENTIONAL ACTION: IMPROVEMENT OF IDEOMOTOR APRAXIA USING THE MIRROR BOX[5]

6.1. INTRODUCTION

In the present study, we tested a novel rehabilitative setting based on the conceptualization of IMA as a defective access to the body schema (Buxbaum et al., 2000; Canzano et al., 2016; Georg Goldenberg, 1995; Sunderland & Sluman, 2000). The working hypothesis is that modulating body representation may result in an improvement of apraxia. To this aim, we employed a modified version of the mirror box setup. The core mechanism accounting for the efficacy of the mirror box might be the process of embodiment of the patient's healthy hand seen in the mirror, which improves body representation (Liu & Medina, 2017; Romano, Bottini, et al., 2013). This process would, in turn, modulate sensory-motor processing in the hand hidden in the box, as shown in both healthy (Bultitude et al., 2016; N. P. Holmes et al., 2004; Liu & Medina, 2017; Romano, Bottini, et al., 2013) and brain-damaged participants (Romano, Sedda, et al., 2013; Tosi et al., 2018). Critically for the working hypothesis is that such an improvement of the body schema would positively affect the programming of motor plans, eventually improving IMA.

Furthermore, we assessed whether the MB procedure induced a modulation of subjective body metric.

6.2. MATERIALS AND METHODS

6.2.1. Participants

The general criteria to be included in the study were having a pathological performance at De Renzi test for IMA (De Renzi et al., 1980), and the ability to comprehend simple verbal instructions, such as those required by the rehabilitative tasks. The second criterion was tested using the token test (De Renzi & Faglioni, 1978). If participants were not able to complete the first block of orders, they were excluded from the study. Additionally, excluding criteria were also having a severe general clinical condition that limit the compliance with the physical therapy and having had multiple stroke events. From the sample of 20 patients that underwent the first assessment for apraxia, one patient was excluded because of premorbid severe clinical conditions (drug addiction, kidney and heart problems), and one was excluded because of a neurological motor impairment preceding the stroke. Two more patients were excluded because of severe deficits in language comprehension with deficits in the comprehension of simple requests. Finally, three more patients were excluded after the second baseline

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assessment, one week after the first one (see below), because they showed large spontaneous recovery that would make any treatment-based improvement unreliable. Thus, the final sample was composed by 13 patients (age: 64 (average) ±7.71 (StDev); education: 9.58±3.92) presenting with IMA. Patients were treated and evaluated by two neuropsychologists, members of the authors team (GT in Somma Lombardo, VG in Negrar).

Patient #2 did not complete the third week of training, so she was excluded from the analysis carried out to test the efficacy of rehabilitation (see methods below). Finally, patient #10 was not able to understand the task for the measure of body representation (see methods below), so he did not complete that task. Thus, we had a sample size of 12 patients for the rehabilitation analysis, 12 for the body representation analysis, and 11 for the correlation analysis.

Twelve patients presented with a left-brain lesion, while one subject had a right hemisphere lesion (#P5). Brain imaging of patients #2, #7, #12, #13 was not available, so that lesion mapping was done on a total of eight left-brain damaged patients.

The study was approved by the local Ethics committees and was done in agreement with the declaration of Helsinki (World Medical Organization, 1996).

Id	Age	Education	Lesion Site	Hemisphere	Time of the TC/MRI from the Stroke	Time of T0 from the Stroke	First Condition of Training
P1	52	8	FP	L	2709	7.4 years	Imitation
P2	75	5	--	L		Stroke date not available	Mirror
P3	67	11	FTP-bg	L	39	1.47 years	Mirror
P4	67	18	FT-Ncap	L	13	95 days	Imitation
P5	65	5	FTP	R	13	265 days	Mirror
P6	74	5	T	L	28	82 days	Mirror
P7	70	8	FTP	L		79 days	Imitation
P8	65	13	TP-PO	L	71	22 days	Imitation
P9	46	13	T-Ncap.	L	87	51 days	Mirror
P10	64	8	FTP	L	46	87 days	Imitation
P11	66	11	FTP	L	14	31 days	Imitation
P12	69	5	P	L		40 days	Mirror
P13	63	10	P	L		103 days	Imitation

Table. 6 Clinical and demographic information of patients. Age and education are reported in years. Lesion site is taken from the medical records of patients and is described by a specialist in neuroradiology. F=frontal lobe, P=parietal lobe, T=temporal lobe, O=occipital lobe, bg=basal ganglia; L=left, R=right.

6.2.2. Procedure

Patients were tested at baseline in sub-acute or chronic phase (i.e., more than three months from the acute event) except #P8 who was tested at 22 days from the acute event (T0 - Baseline). The presence of IMA was formally assessed by the De Renzi test (De Renzi et al., 1980). Patients were re-tested after one week during which rehabilitation for sensory-motor deficits was provided, according to

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the standard protocol in use of the hospitals, which did not include any specific treatment for apraxia (T1 - Rest). These treatments consisted of two daily one-hour sessions of physiotherapy. The second baseline assessment was included to evaluate the degree of spontaneous recovery from IMA. This week was followed by two weeks of alternative treatments, each one followed by the re-testing of apraxia (T2, T3). One week featured the experimental protocol with the mirror box training (Mirror). The other week comprised a largely used restorative approach to apraxia, namely the imitation of a series of actions of increasing difficulty (e.g. Nicola Smania et al., 2000b), which were performed by the experimenter, who was sitting in front of the patient (Imitation). The order of Mirror and Imitation weeks was balanced across participants (Table 6): six patients did mirror rehabilitation first, and seven did imitation first.

Additionally, on the first day of mirror box treatment, patients were assessed by means of an additional task investigating whether or not the mirror box procedure modulated body representation (see below).

Finally, for those patients in which brain scans were available, brain lesions were mapped and analysed using a maximum overlap procedure and a Voxel-Based Lesion Symptom Mapping (Bates et al., 2003).

Assessment of Ideomotor Apraxia

The assessment of IMA was always performed on the patient's hand ipsilateral to the lesion side in order to exclude the effects of other lower level motor deficits, potentially present in the hand contralateral to the lesion side. IMA was tested using the protocol designed by De Renzi (De Renzi, Motti, & Nichelli, 1980), consisting in the imitation of 24 different movements. Half of these movements are meaningful (e.g., thumb and index fingertips touching as to mean "ok") and half are meaningless (e.g., thumb in between of the index ad middle finger). Half require to hold a stationary posture (e.g., index finger extended up, with the other fingers flexed), and half require the execution of a motor sequence (e.g., open and close the index and middle fingers like scissors). The patient has to imitate the gesture demonstrated by the examiner who is in front of him/her (Figure 13a). In case of failure, the action can be repeated up to three attempts. Trials are scored 3 if the gesture is executed correctly at the first attempt, 2 at the second attempt, 1 at the last attempt and 0 if it cannot be executed correctly. Thus, the total test score ranges from 0 to 72. The cut-off scores are 53, for clear deficit and 61 for borderline performance.

Assessment of Body representation following MB procedure

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The modulation of subjective body metric was assessed by asking the participants to perform the same bisection task used in Experiment 4 (Rossetti et al., 2019; Giorgia Tosi, Romano, & Maravita, 2018).

The task was performed before and after two conditions of mirror visual feedback congruency. In both conditions, patients had to look into the mirror, where the examiner's hand was reflected, while keeping their hand contralateral to the lesion side hidden inside the mirror box. Both the examiner and the patient were requested to do simple tapping-like movements with the index finger. The two movement conditions, each lasting 120 seconds, differed for the experimenter's posture which was anatomically congruent (Anatomical condition, Figure 13b) to the patient's hidden arm, or rotated by 90° (Control condition), thus in an anatomically incongruent posture (Figure 13c). While the first condition may induce embodiment, the second is unlikely to do so (Pavani et al., 2000; Romano et al., 2016a).

Each patient performed 40 bisection trials: 10 pre-tapping Anatomical, 10 post-tapping Anatomical, 10 pre-tapping Control, 10 post-tapping Control. The entire procedure lasted less than 10 minutes and was done on the first day of the Mirror Box training week only.

Mirror Box Rehabilitation program

The specific rehabilitation program consisted in 20 minutes MB sessions during which the patient hid either his/her right or left hand behind the mirror (10 minutes each) while a trained experimenter put one of her own hands in front of the mirror, so as to generate a mirror reflection which was visually congruent to the hidden hand (Figure 13b). Given that apraxia typically affects both arms, we modified the standard mirror box protocol, so that the hand reflected in the mirror was that of an experimenter, and not the hand of the patient him/herself. In this situation, the patient was invited to simultaneously try to perform the same hand or finger movements that he/she saw performed by the examiner in the mirror. This ensured that the patient received a visual feedback from correctly executed movements. The motor sequences were custom made, involved either the fingers or the whole hand. These movements were selected to be of gradual difficulty and to be different from those used in the standard tests for IMA. Each movement started after a verbal description of the motor sequence by the experimenter (e.g. "Please, move up and down the middle finger, once per second"). Each movement was performed continuously for about thirty seconds and was then followed by a new movement, after a brief interval.

The same gestures and session duration were used for the Imitation therapy condition (Figure 13a). In the imitation treatment, the experimenter was sitting in front of the patient, who was requested

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to imitate each gesture performed by the examiner, similarly to previously published protocols for apraxia rehabilitation (Nicola Smania et al., 2000b). The 20 minutes training sessions were performed in addition to the routine daily physiotherapy activity of each rehabilitation unit, at a different time in the day.

The assessment of apraxia was performed at the end of the last day of each treatment week and it was separated from the training session, the standard physiotherapy or speech treatment session, so that it did not immediately follow any training.

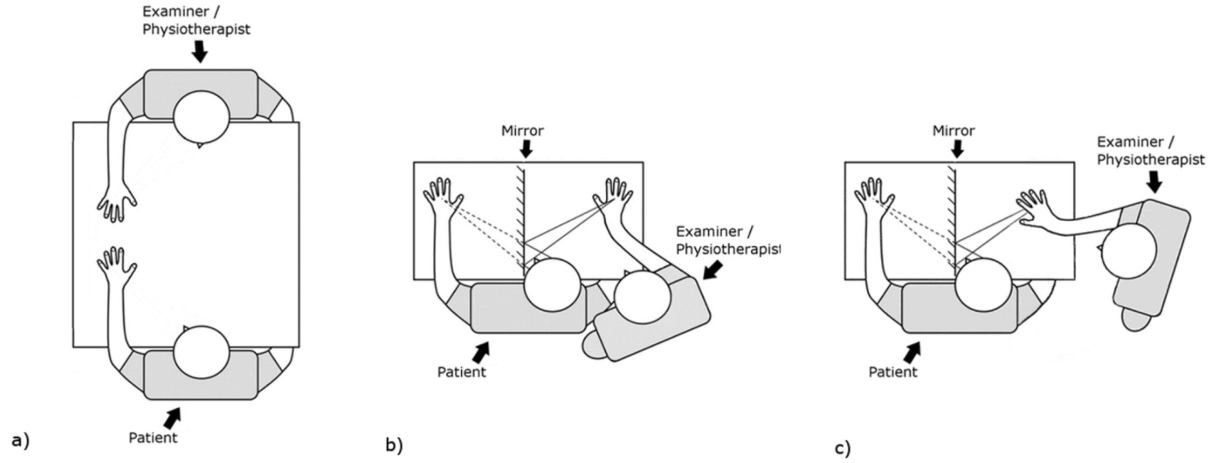

Figure 13. **Schematic representation of the different situation adopted during the study.** a) shows the situation used during the assessment of apraxia for the evaluation of the efficacy of rehabilitation. The same situation was used during the Imitation training week. b) shows the situation adopted during the Mirror training week. The same situation was used during the assessment of body representation changes induced by the mirror box procedure. This condition is the one defined "Anatomical" were the mirror reflection of the examiner's hand overlaps with the visual position of the patient's hand hidden in the mirror box. c) represents the other condition used to test the body representation changes induced by the mirror box. This is the condition defined "Control" where the hand seen in the mirror by the patients is visually misaligned with the hidden hand. The 90° rotation of the examiner's hand produce a mirror image that is anatomically implausible with patient's hand.

Brain Lesion Mapping

A trained researcher (GT) mapped lesions on the reconstruction of the original neuro-imaging study. The CT scans of 9 out of 13 patients were available for lesion mapping. Each image was manually reoriented by means of software SPM12 (Ashburner et al., 2013). Brain lesion mapping was subsequently done using the software MRIcron (MRIcron, 2009; Chris Rorden, Karnath, & Bonilha, 2007). For each subject a file from the Region of Interest (ROI) was created. CT scan and relative ROI were then normalised to a standard template, using the Clinical Toolbox in SPM (Christopher Rorden, Bonilha, Fridriksson, Bender, & Karnath, 2012).

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6.3. ANALYSIS

Rehabilitation

We first calculated the degree of improvement following each of the two weeks of rehabilitation. We subtracted the patients' score obtained in De Renzi test (assessing IMA on the hand ipsilateral to the lesion site to rule out the potential confound of low-level motor dysfunction) at the end and at the beginning of each week (T1-T0, T2-T1 and T3-T2). We then used a series of Bayesian t-tests (Rouder, Speckman, Sun, Morey, & Iverson, 2009) as implemented in JASP 0.8.6 (JASP Team - 2018) to compare the effectiveness of the different trainings. We adopted default parameters (i.e. a non-informative prior with a Cauchy distribution with a scale of .707). Additionally, we ran sequential analyses that test the strength of the evidence in favor of one or the other hypothesis after each data entry, in order to gain indications for the stability of the effect. If the effect is consistent across the patients, then the Bayes Factor (BF) tends to increase progressively by adding new data in the analysis.

We performed Bayesian t-tests comparing the variables Imitation to Rest, Mirror to Rest, and Mirror to Imitation. The dependent variable was the change at the De Renzi test score, namely the improvement reached at the end of the week of treatment.

We additionally performed an overall one-way repeated-measure ANOVA with the factor Treatment comprising: Rest, Imitation and Mirror levels. The ANOVA was followed up with post-hoc tests adopting Bonferroni-Holm correction.

Body representation assessment

A percentage score was calculated for each forearm bisection trial as Experiment 4. A value higher than 50% indicates a deviation of the subjective midpoint towards the elbow, i.e. proximal deviation. A value lower than 50% indicates a deviation towards the hand, i.e. distal deviation (Garbarini et al., 2014; Romano et al., 2018; Sposito, Bolognini, Vallar, Posteraro, & Maravita, 2010; Tosi et al., 2018), thus a perfect performance is 50% and any shift toward this value can be considered an improvement. The experimental design to evaluate body representation modulation with the bisection task is a 2*2 within-subject design including the independent variables: time (pre-/post-training) and posture condition (Anatomical/Control).

For the analysis, we adopted a linear mixed model (LMM) design including the patients as random effect variable and time and posture as a full factorial fixed effects design. Analysis of Variance with Satterthwaite's method was used to estimate significance of fixed effect designs. LMM analysis was done using lme4 package for the software R (R Core Team 2016). Post-Hoc testing was performed using the package PHIA.

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The parameter estimated for the random effect of the time*posture interaction was used as individual index of body representation change for correlation analysis, because it reflects the strength of the interaction at individual level.

Correlation analysis

We took the parameter obtained from the random effect estimation of time*posture interaction as individual index of body representation change and we put it in relation to the recovery index for each week of treatment. We calculated the Spearman's rho as correlation index of the relation between body representation change and the degree of improvement for each condition of treatment.

Lesion Mapping

We first created the overlap map of the eight left-damaged patients using MRIcron. Since #P5 had a right hemisphere lesion, it was excluded from the analysis.

Then we performed an exploratory voxel-based lesion–symptom mapping (VLSM) on the normalized lesion maps, in order to analyze the relationship between voxel damaged and behaviour on a voxel-by-voxel basis (Bates et al., 2003). The predictor was the subjects' performance at the De Renzi test at T0.

VLSM was conducted using NPM package, distributed with MRIcron (Rorden et al., 2007). We used the ch2.nii MRIcron template (Holmes et al., 1998) and set a 10% threshold of the lesioned voxel (i.e., each damaged voxel was tested). For this analysis, we adopted an exploratory approach to maximize the probability of highlighting the lesion pattern associated with poor performance at the apraxia test. We thus used Brunner-Munzel test with no permutations and uncorrected thresholds ($p < 0.05$) to determine the voxels damaged predicted by the low performance at De Renzi test. The limited sample size of our study suggests taking the results of the voxel-wise analysis very cautiously, nonetheless we believe that this is an issue that deserves to be explored forming a first evidence that will need further specific investigations.

6.4. RESULTS

Rehabilitation

The Bayesian t-tests showed extremely strong evidence (BF_{10}=129.77) in support of the effectiveness of the Mirror rehabilitation (average of improvement ± StErr =11.25±1.71) as compared to Rest (-2.5±1.39). Additionally, we obtained moderate evidence (BF_{10}=7.29) in support of a better results achieved with the Mirror rehabilitation as compared to Imitation (2.75±1.45). Finally, we found no substantial evidence (BF_{10}=1.71) in support or against the effectiveness of Imitation vs Rest.

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The ANOVA revealed a significant effect of the factor treatment (F(2,22)=15.099, p<.001, η²=.579). Post-hoc comparisons showed significant differences between Mirror Vs Rest (p<.001), and Mirror Vs Imitation (p=.015). The comparison of Imitation Vs Rest was also significant, although it is close to the conventional limit of significance .05 (p=.048). Overall (as shown by Figure 14), we can conclude that Mirror rehabilitation induced a larger degree of recovery than the other two conditions. Imitation also showed to be effective as compared to Rest; however, this effect looks smaller and less consistent.

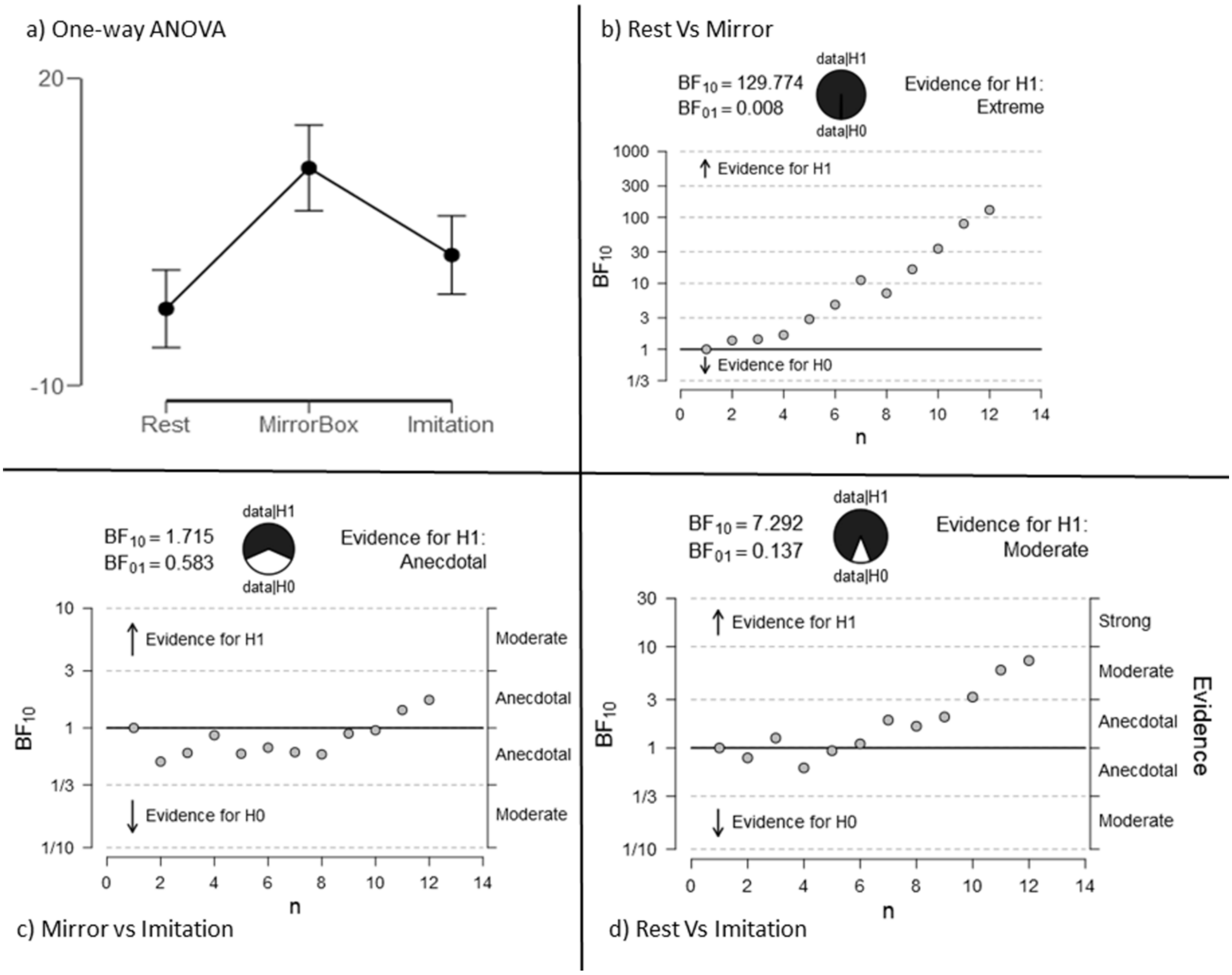

Figure 14. **Rehabilitation results**. **Panel a** report the mean and the 95% confidence interval of each condition of treatment. The other panels report the results of the Bayesian t-tests and the sequential analysis. The value of the BF and the strength of the evidence in favor of H1 are reported in the upper part of each panel. The graphs represent the BF value after each data entry. The more data (i.e., more information) the strongest the conclusion in favor of the Mirror as compared to both Neutral (**panel b**) and Imitation (**panel d**) conditions. **Panel c** shows that a strong claim about the efficacy of Imitation treatment canot be taken, sequential analysis furtherly support the instability of this comparison.

Body representation

ANOVA on the fitted Linear Mixed Model highlighted a significant main effect of time (F(1,11.023)=4.802, p=.05) and a significant interaction of time by posture conditions

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(F(1,11.034)=5.219, p=.043) as shown in Figure 15. The main effect of posture condition was not significant (F(1,10.989)=.0876, p=.772).

Post-hoc tests showed that a difference between pre-tapping and post-tapping was significant for the Anatomical condition (p=.012) but not for the Control condition (p=.845). The arm was bisected significantly more distally (i.e., toward the hand, closer to the correct position) after the tapping with the Anatomical posture (pre:=67.3%±2%; post=63.4%±2.6%), but not with the non-anatomical control posture (pre=65.8%±1.6%; post=65.6 ±.1.78%), suggesting an effect of the mirror box in modulating body representation in the former, but not latter condition.

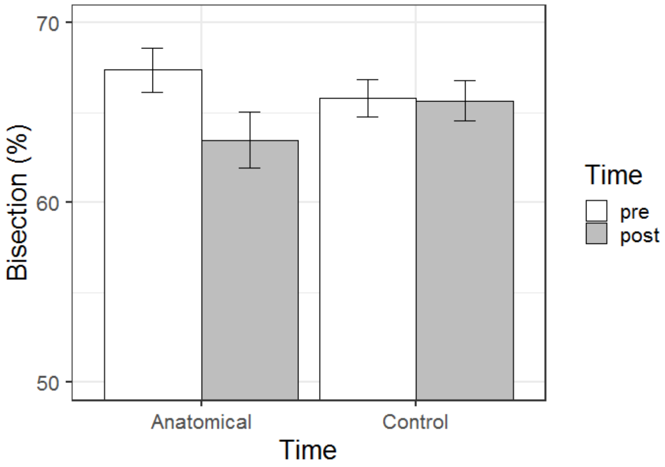

Figure 15. **Body representation results**. The figure shows the interaction between time and posture.

Correlation analysis

A significant positive correlation was found between the body representation index and the recovery achieved with the mirror (rho=.620, p=.042), suggesting that the stronger the former, the higher the latter. The relation of body representation change with the other two conditions of treatment is non-significant and, if anything, shows an opposite trend (imitation: rho=-.301, p=.368; rest: rho=-.236, p=.486).

Lesion Mapping

The overlap of lesion mapping of the eight patients revealed an involvement of a Fronto-Parietal network in the left hemisphere as shown in Figure 16. The maximum overlap (five patients) was identified in the frontal operculum and the corona radiata. Other areas of interest (three to four patients overlapping) include subcortical structures (basal ganglia, thalamus, hippocampus and insula) and part of the temporal lobe along with the involvement of white matter tracts of the internal and the external capsule.

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Coherently, the Voxel-Based Lesion–Symptom Mapping, using the De Renzi scores at T0 as predictor, revealed a relation between the performance in the apraxia test and a cluster of voxels in the frontal operculum and the anterior corona radiata in the left hemisphere (Figure 16). Once again, VLSM results must be read with careful consideration.

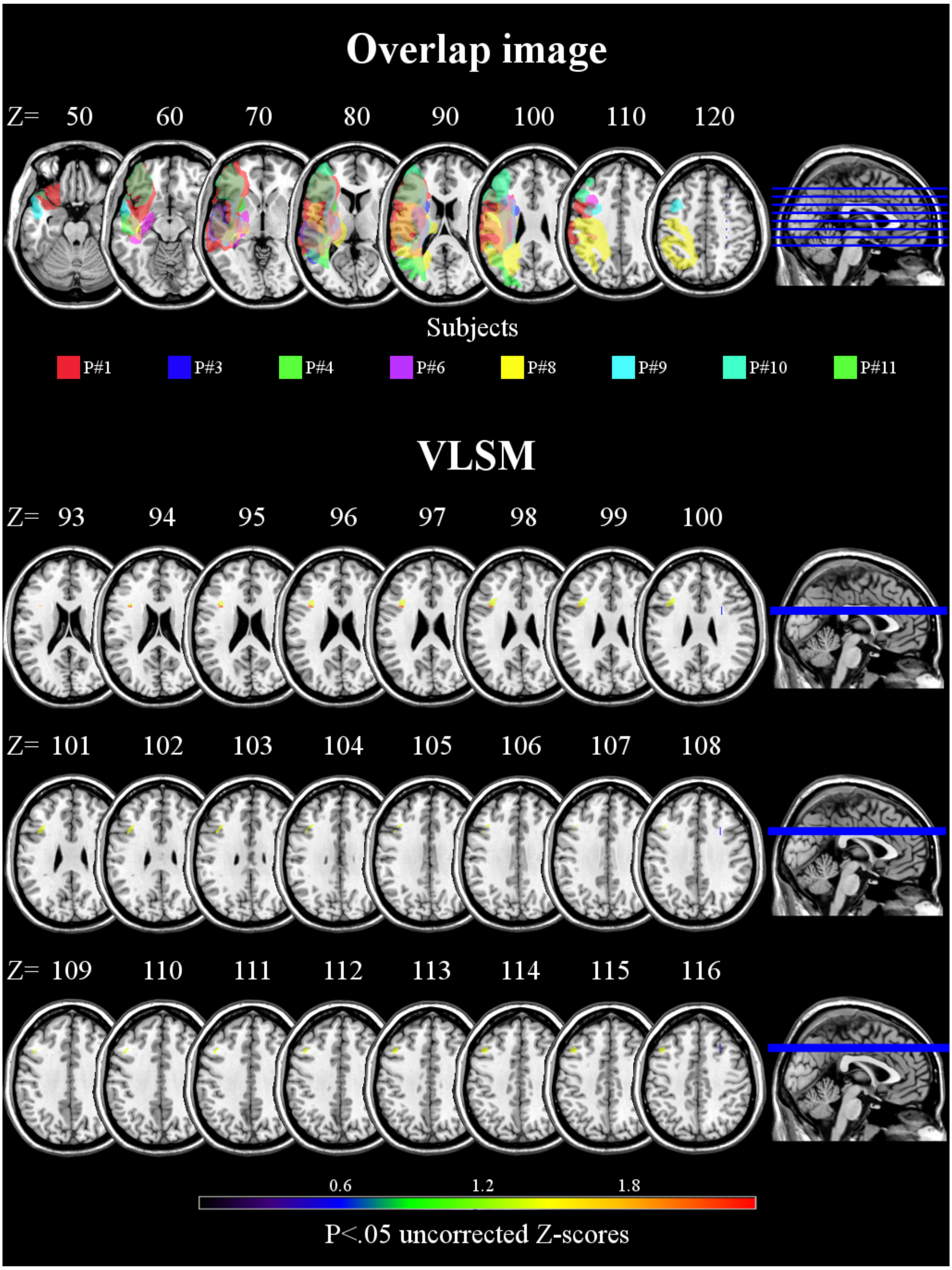

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Figure 16. **Lesion mapping results.** The upper part of the figure shows the overlap of lesions in our sample, we characterized each patient with a different colors. An extended left Fronto-Temporo-Parietal network involving both cortical and subcortical regions emerges to be frequently damaged in our sample. The lower part of the figure shows VLSM results, highlighting a crucial association between the IMA performance and a lesion in the left corona radiata and left frontal opercular cortex. All the slices with a significant voxel are reported. VLSM adopted the performance at De Renzi test at T0 as predictor and using the Brunner-Munzel test with no permutations and uncorrected thresholds ($p < 0.05$).

6.5. CONCLUSION

The present paper describes a novel experimental rehabilitative protocol for IMA based on the mirror box technique. Furthermore, our results also inform the theoretical discussion around IMA suggesting for a role of the body schema in recovering from the deficit.

In our custom-made version of the mirror box paradigm, patients observed the mirror reflection of the examiner's performing a series of movements and were instructed to perform the same movements with the affected hand hidden inside the box.

In the literature, it is possible to identify two main approaches to IMA rehabilitation. On one side, restorative methods, which aim at recovering the ability to execute impaired movements (G Goldenberg & Hagmann, 1998; Georg Goldenberg, Daumüller, & Hagmann, 2001; N Smania et al., 2006; Nicola Smania et al., 2000a). On the other side, compensatory methods focus on the goal of an impaired action in order to try alternative ways to achieve it (Geusgens et al., 2006; van Heugten, Dekker, Deelman, Stehmann-Saris, & Kinebanian, 2000; van Heugten et al., 1998). Both approaches seem to yield some improvement for upper limb apraxia, despite very limited available literature (Cantagallo et al., 2012).

The procedure that we used may be classified as a restorative method and was inspired by the well-known rehabilitative approaches using the mirror box (Ramachandran & Altschuler, 2009). In typical mirror box paradigm, patients look at the reflection of their own unaffected limb in the parasagittal mirror, while sending symmetrical motor commands to that limb, as well as the limb hidden behind the mirror (or the stump in the prototypical case of amputees). This treatment is known to ameliorate pain sensations in case of phantom limb pain or chronic pain syndromes (MacLachlan, McDonald, & Waloch, 2004; Ramachandran, 1996; Ramachandran & Altschuler, 2009; Ramachandran, Rogers-Ramachandran, & Cobb, 1995), as well as motor performance (Altschuler et al., 1999; Romano, Sedda, et al., 2013; Yavuzer et al., 2008) and body metric representation (Experiment 4) after stroke.

A critical difference between our procedure and the classic mirror box is that the moving hand reflected in the mirror was not that of the patient but belonged to an experimenter. This change was introduced to ensure a visual feedback from correctly executed movements, given that apraxia often affects limbs on both sides.

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We found that a single week of mirror box training significantly improves IMA as compared to one week of rehabilitation following frontal imitation – i.e., a procedure previously adopted for treating this condition (Smania et al., 2000a), or one week of unspecific rehabilitation.

From the clinical point of view, the present approach is particularly well suited for the rehabilitation of IMA. First, this is a very low-cost procedure, so that it can be easily implemented in any rehabilitative or domiciliary environment. Second, the proposed protocol proved effective in generalizing to movements that were different for both the motor sequence (being tested with untrained motor sequences) and the testing situation required (i.e., frontal imitation as compared to first person perspective). Third, given the excellent compliance shown by patients in fulfilling the experimental sessions, the procedure could be conveniently adopted to design longer trainings in case this would be needed to achieve a larger and more stable recovery. Notably one week proved to be enough to trigger an initial benefit, a very quick and desirable effect. In comparison with previously published data, the effect we observed seems to be at least comparable to other currently available approaches that require longer periods of treatment (see for a review Cantagallo, Maini, & Ida, 2012).

The superiority of the present training in respect to those based on imitation in third person perspective (Smania et al., 2000b) could be due to the different brain mechanism recruited. Based on previous research, is plausible to think that the process of embodiment, typically generated by the mirror box, could be critical to favour the improvement of motor programming. Observed movements in a third person perspective (Imitation) are likely to induce imitative premotor activations, that may trigger motor programs akin to those observed (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995). However, they never induce such strong subjective, illusory feelings of ownership of the observed moving part, such as those induced by a mirror box setting. Our results support the idea that the vision of the anatomical hand in the mirror is embodied, thus positively impacting body representation, in line with what found with patients with hemiplegia (Tosi et al., 2018; Zampini, Moro, & Aglioti, 2004). This modification is in line with the idea that the mirror box works because the hand seen in the mirror goes toward an embodiment process (Romano, Bottini, et al., 2013; Rossetti et al., 2019), possibly because of a reconstructed bottom-up visuo-motor congruency between motor intention and the visual feedback of the executed action (Ramachandran et al., 1995). These results suggest the possibility that the vision of the examiner's hand in a congruent position by respect to the patient's hand is incorporated into patient's body representation. Since the observed hand is executing flawless movements, also these movements would be embodied. This embodiment of a hand-in-action probably triggers a process of planning and executing correct actions, either by correcting disrupted motor programming or by triggering existing motor programs that would not be correctly recruited due to brain damage.

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Recent experimental evidence supports the idea that mirror box alters body representation of the limb hidden behind the mirror by showing that the reflected arm impacts action execution with the arm inside the box (Holmes, Snijders, & Spence, 2006), as well as tactile (Bultitude et al., 2016) and proprioceptive processing (Romano, Bottini, et al., 2013). Moreover it was also shown that the mirror reflection of an alien hand (e.g., such as that of the experimenter in our paradigm) can produce ownership sensations (Takasugi et al., 2011).

On a similar token, mirror box showed to alter action performance in cases of Alien Hand Syndrome. Patients had a significant improvement of the motor control of the alien hand when it was inside the mirror box and they observed in the mirror, correct movements coming from the unimpaired arm, mimicking the posture of the impaired one (Moro et al., 2015; Romano, Sedda, et al., 2013).

Those preliminary findings, together with the current results, support the idea that the hand seen in the mirror may trigger the incorporation of sensory motor functionality overwriting, to some extent, the information coming from the hidden impaired limb. In the specific case of this study, we propose that the embodiment of the experimenter's hand together with its functionality, replaces the representation of the affected hand inside the box, biasing (i.e., improving) sensory-motor processes. To better investigate the relation between mirror box effectiveness and changes in body representation, we first used an experimental procedure to quantify changes in body representation induced by the mirror box (Tosi et al., 2018) and we then correlated that index with the effectiveness of the treatment. We observed changes of body representation induced by the mirror box, as witnessed by the improvement in the forearm bisection task, an experimental procedure that is sensitive to body representation changes (Rossetti et al., 2019; Tosi et al., 2018) and embodiment effects (Sposito et al., 2012, Garbarini et al 2015). Indeed, following a short training with the mirror box facing the arm in an anatomical posture, but not following the training with the arm in a non-anatomical posture, patients bisected their own limb toward a more correct position. MB training enhance patients' precision in body metric estimation, suggesting an effect of the embodiment process over the representation of their limb.

Previous studies have shown the efficacy of a mirrored vision of self in disorders of body awareness, in particular in anosognosia for hemiplegia and somatoparaphrenia (Besharati et al., 2014; Fotopoulou et al., 2011). Interestingly, those studies indicated that changing the perspective of body observation (from a first to a third-person perspective) can induce a recovery of symptoms, with better recognition of the paralysis and an increase in the sense of ownership towards the affected limb (Besharati et al., 2014; Fotopoulou et al., 2011). However, in those experiments the patients observed

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themselves in a static situation (or during a failure in the attempt to move their arm), while during the mirror box therapy they were asked for continuous and repeated attempts to move their limb. Two, not mutually exclusive, hypotheses may underlie the effect of different perspective on the diverse deficits. In the mirror box training, the mirrored embodied arm shows a correct movement that interacts with patient's motor plan overwriting the incorrect motor plan and promoting the recovery of apraxic symptoms. A second possibility is that in apraxic patients, who do not suffer from body awareness disorders, the embodiment of the examiner's arm allows the recovery by accessing the spared functions of the body schema. On the contrary, in patients who actually suffer from a body awareness disorder, a disembodied view of their own paralysed limb (i.e. from an external viewpoint, a third-person perspective) may offer an alternative way to access body representation, without relying on the self-centered representation of the body schema that is likely to be impaired or inaccessible (Romano & Maravita, 2019).

Importantly, the changes in body representation induced by the mirror box positively correlated with the recovery achieved with the mirror treatment, suggesting that the stronger the body representation change, the larger the effect of mirror box treatment. Anecdotal observations also suggest that the hand seen in the mirror was actually embodied by the patients as some of them reported spontaneously that they felt like they were looking at their own hidden limb instead of the experimenter's limb.

A final comment is for the lesion mapping analysis that revealed the involvement of a Fronto-Parietal network of the left hemisphere. In our sample, it seemed that the frontal operculum and the white matter tract of the corona radiata were particularly crucial for IMA. These findings are in line with the literature that associates apraxia with cortical and subcortical fronto-parietal lesions in the left hemisphere (Goldenberg, 1995; Niessen, Fink, & Weiss, 2014). Interestingly, it was shown in stroke patients that the mirror box illusion involves the activation of the posterior cingulate cortex and the precuneus, areas associated with the self-awareness and spatial attention (Michielsen et al., 2010). Crucially those areas look spared in our sample, suggesting that their recruitment was available and supporting the mediation of embodiment for the effectiveness of the method.

In conclusion, the effectiveness of mirror box treatment suggests a significant relationship between IMA and body schema. From an epistemological perspective, the present work offers a promising theoretical and practical framework for the understanding of IMA and its improvement.

From a clinical perspective, the surprisingly positive improvement obtained with such a simple and handy technique like the one described here, offers a very positive perspective for the treatment of this very disabling neuropsychological condition.

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7. EXPERIMENT 6. BODY ILLUSION AND AFFORDANCES: THE INFLUENCE OF BODY REPRESENTATION ON THE PERCEPTION OF SPACE[6]

7.1. INTRODUCTION

Although a series of studies confirms that the influence of our body on objects and space affects the way individuals perceive themselves interacting with the environment, it remains unclear whether or not an altered (experimentally induced) body perception could have a significant impact on the way individuals perceive their interaction with the spatial surrounding. That is the aim of our study. Specifically, we tested the hypothesis that an altered body representation could modify the way individuals perceive their interaction with the surroundings. To test this hypothesis, we used a Full-Body Illusion-like paradigm to induce the ownership of longer legs compared to normal size ones, and asked participants to then perform a time-to-walk estimation task with targets presented at different distances in a virtual environment (Klein et al., 2009; Plumert et al., 2005).

7.2. MATERIALS AND METHODS

7.2.1. Participants

We recruited 41 healthy volunteers (38 females, mean age 20.12±2.34 years, range 17-30 years; mean education 13.78±1.46 years, range 12-18 years) through the Research Participation System of the Psychology Department of the University of Calgary. In order to calculate the a priori sample size of participants to be included in the study, we conducted a power analysis with G*power 3.1.9.2. The analysis revealed that in order to obtain a power of 0.95, with alpha set at .05, and effect size at 0.25, we needed to test a total of 36 participants; these effect size and power are consistent with other studies adopting similar embodiment questionnaires (Romano et al., 2014, 2016).The study was approved by the University of Calgary Conjoint Faculties Research Ethics Board (CFREB18-1494). Informed consent was obtained from all individual participants included in the study.

7.2.2. Procedure

Participants underwent two testing sessions in two different days, with a washout week. In each testing session, participants were exposed to the Body Illusion presented in Experiment 3 and were required to perform an imagery walking task in a virtual environment. To control for the individuals' natural variability in walking speed, and for a faster walking pace in the virtual environment (Kelly, Donaldson, Sjolund, & Freiberg, 2013; Klein, Swan, Schmidt, Livingston, & Staadt, 2009; Plumert, Kearney, Cremer, & Recker, 2005), we asked all participants to undergo a walking speed test in a virtual and a real environment before performing the imagery walking task.

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[6] This chapter is based on the paper by Tosi, G., Parmar, J., Dhillon, I., Maravita, A., &Iaria, G. Body illusion and affordances: the influence of body perception on space interaction (under review)

Walking speed test

The walking speed test was performed in both the real and the virtual environment, following a standard procedure as adopted in previous studies (Klein et al., 2009; Plumert et al., 2005).

In the real environment, the test consisted of four trials. In each one, subjects were asked to stand in a corridor facing a pylon located at 15m of distance from their position. Participants were asked to reach it by walking at their average pace. We used this task to get a baseline measure of the participants' speed walking in order to compute the estimation error during the imagery walking task. Since the aim of our study was not to compare the walking time in a real and a virtual environment, we did not reproduce the real environment in VR.

The virtual environment used to perform the imagery walking speed test was developed with Unity (2018 Unity Technologies) and consisted of an empty desert-like landscape (see Figure 17). The walking speed test in the virtual environment consisted of six trials. Since in VR there are fewer landmarks and depth cues as compared to the real environment, we decided to include more trials to have a more reliable estimation of participants' time-to-walk as suggested in the literature (Klein et al., 2009; Plumert et al., 2005). In each trial, participants were asked to look at a pylon located at 15m (see Figure 17), as in the real environment. However, in this case, it remained visible for five seconds, after which participants were asked to reach its location. The removal of the visual target cue (pylon) is a standard procedure for evaluating walking speed in virtual environments given that visual information is mostly processed for solving the task (Klein et al., 2009; Plumert et al., 2005). In both the real and the virtual environments, we measured the time that subjects spent to reach the pylon's location.

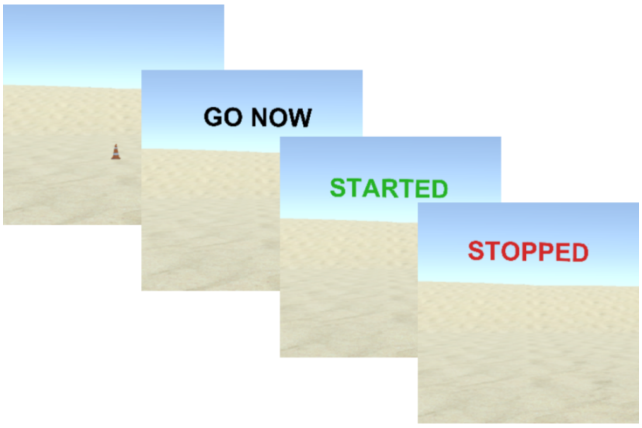

Figure 17. **Walking speed test and Imagery Walking Task procedure.** The figure shows one block of the Imagery Walking Task: participants were shown a pylon for five seconds; after the pylon disappeared, the text "GO NOW" appeared on the screen to indicate participants that they could have pressed the button to start imaging the walking towards the previously seen pylon. As soon as participants pressed the button to start the imagery walk, a green text saying "STARTED" appeared on the screen. When subjects reached the target location in their imagery walk, they were required to press the same button used to indicate the starting time, and a red text saying "STOPPED" appeared on the screen

Body illusion

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To create the body illusion, we adopted a similar procedure as in Experiment 3 that combines visual and tactile information (Kilteni, Normand, Sanchez-Vives, & Slater, 2012; Romano, Pfeiffer, Maravita, & Blanke, 2014; Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010; van der Hoort et al., 2011). The visual component of the illusion required participants to watch a 360° video presented in a set of Head-Mounted Displays (HMDs – Oculus Rift, 2018 Oculus VR, field of view = 110°, resolution per eye = 1080 x 1200, 6 degrees of freedom head tracking). Videos were recorded with a 360° camera (Samsung Gear 360 (2017) - features: CMOS 8.4MP x2 / F2.2 lens; video recording resolution: 360° Dual Lens: up to 4096 x 2048 (24fps) so that it was possible for the participant to visually explore the environment during the video presentation. The procedure was the same as in Experiment 3, except that we created two new videos, one displaying averaged legs' length (108 cm) and one displaying a pair of longer legs (203 cm), both presented in anatomical (Figure 18a, c) and non-anatomical (Figure 18b, d) orientation. We showed each video four times, each time followed by four trials of the Imagery walking task.

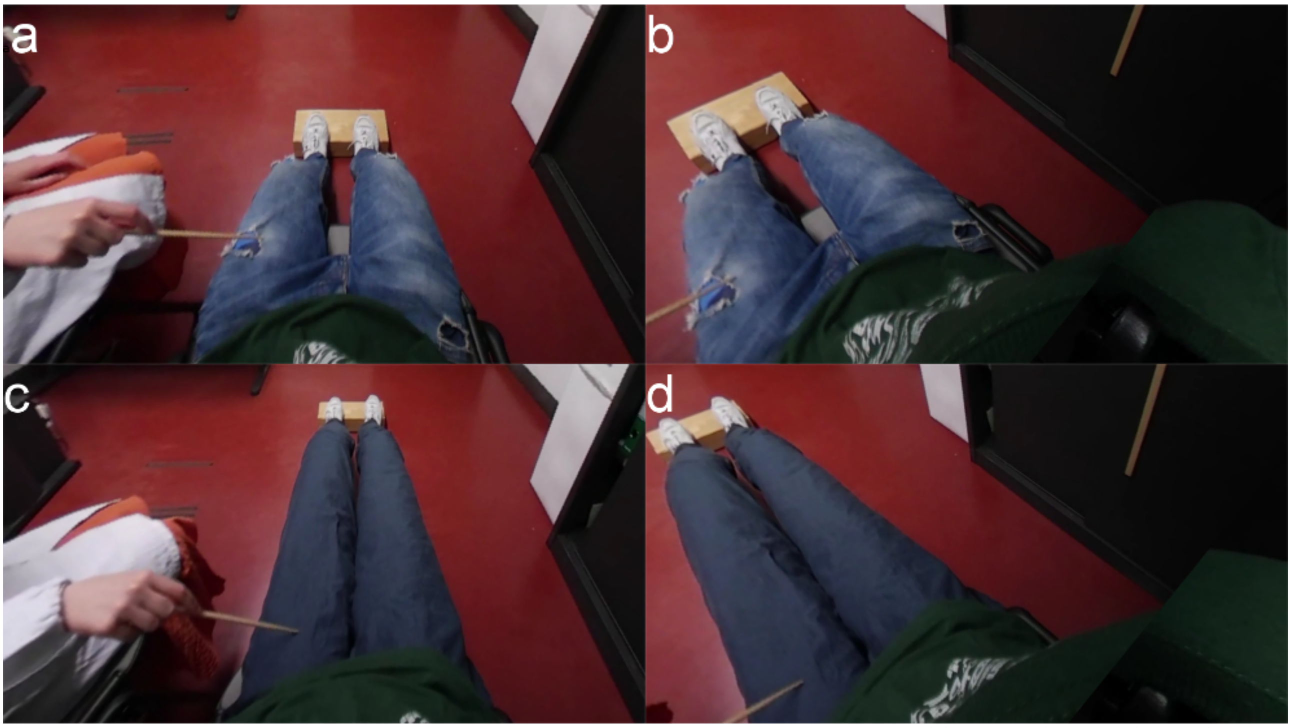

Figure 18. **Full-Body Illusion-like paradigm.** The figure shows four frames extracted by the videos used to induce the body illusion. Panel a: standard size legs showed in the anatomical orientation. Panel b: standard size legs showed in the non-anatomical orientation. Panel c: long legs showed in the anatomical orientation. Panel d: long size legs showed in the non-anatomical orientation.

Imagery walking task

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The virtual environment used to perform the imagery walking task was the same as for the imagery walking speed test (see Figure 17). The task was presented using the same set of Head-Mounted Displays used for creating the body illusion as described above. Participants were required to wear the headset while sitting on a chair and were given a controller that was used to time the starting and the ending of the imagery walk by pressing a button. The task consisted of 16 trials divided into four blocks. In each block, participants were shown a pylon at four different distances (6, 12, 18, 24m) administered in a counterbalanced order so that each distance appeared as the first condition in at least one of the blocks. We showed the pylon for five seconds, followed by the text “GO NOW” indicating participants that they could have pressed the button to start imaging the walking towards the previously seen pylon. As soon as participants pressed the button to start the imagery walk, the green text “STARTED” appeared on the screen. When subjects reached the target location in their imagery walk, they were required to press the same button used to indicate the starting time, and a red text “STOPPED” appeared on the screen indicating the end of their imagery walk. Throughout the imagery walk, no movement was displayed on the screen. In each trial, we measured the time spent by participants while performing the imagery walk.

In order to test our hypothesis that the perceived length of the legs as induced by the body illusion will impact the time-to-walk estimation, we first determined the correct amount of time that each participant would have needed in order to reach the pylon located at different distances throughout the Imagery walking task. To do this, we computed the participant’s walking speed by dividing the averaged walking time obtained in the four trials of the Walking speed test in the real environment by the distance walked (15m). We then estimated the amount of time needed by each subject to walk the four distances (6m, 12m, 18m, 24m) by multiplying each distance by the participant’s walking speed. For each distance (6m, 12m, 18m, 24m), we then calculated the percentage of time misestimation based on the real pace, with the following formula: [(judged time – actual time) / actual time]*100

Embodiment questionnaire

At the end of each condition, we evaluated the embodiment of the artificial legs presented in the videos with same questionnaire adopted for Experiment 1 and 3. Data were processed following the same steps, namely the scores were ipsatized and then aggregated to obtain an embodiment score averaging the items: Q1, Q2, Q3, Q4 (reversed), Q5, and Q6. The full questionnaire is reported in Appendix, Table 1.

We expected to replicate our previous results, finding significant effects of both Size and Orientation.

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7.3. ANALYSIS

Embodiment questionnaire

We first assessed the presence of the embodiment in the anatomical condition for both the standard and long legs. To do this, we ran a within-subjects 2 (Legs' Size) x 2 (Legs' Orientation) repeated-measures ANOVA on the averaged ipsatized responses to the embodiment statements.

Imagery walking task

We assessed for any influences of the body illusion on the Imagery walking task by running a Linear Mixed Model (LMM) three-way ANOVAs with the misestimation as the dependent variable. Fixed effect factors were Size (Standard/Big), Orientation (anatomical/non-anatomical), and Distance (6m/12m/18m/24m) as within-subject factors. We set the participants as the clustering variable and fixed 95% Confidence Intervals (CIs). To verify our hypothesis that the perceived length of the legs could impact on the time-to-walk estimation, we expected a significant interaction between Legs' Size and Legs' Orientation.

In addition, we compared the Walking speed tests in both real and virtual environments to assess if the perceived walking time in the virtual environment would be the same as the actual time walked in the real one. This analysis was performed in light of previous studies (Klein et al., 2009; Plumert et al., 2005) confirming an underestimation of the time-to-walk in the virtual environment as compared to a real environment. We run a Linear Mixed Model (LMM) one-way ANOVA with the walking time as the dependent variable, the environment (Real/Virtual) as fixed effect within-subject factor, and the participants as the clustering variable. We fixed 95% Confidence Intervals (CIs), to explore interactions reliably, without running additional post hoc tests (Cumming, 2014).

7.4. RESULTS

Embodiment questionnaire

The within-subjects 2 (Legs' Size) x 2 (Legs' Orientation) repeated-measures ANOVA on the averaged ipsatized answers to embodiment statements revealed a main effect of Size ($F(1,40)= 15.52$, $p\leq.001$, $\eta^2= .28$) and Orientation ($F(1,40)= 8.57$, $p\leq.001$, $\eta^2= .35$), confirming that subjects rated higher values of embodiment with the standard legs (CI: 0.11; 0.35) as compared to the long ones (CI: 0.35; 0.11), and when both legs were presented in an anatomical orientation (CI: 0.11; 0.35) as compared to the non-anatomical one (CI: 0.35; 0.11). We did not find any interaction effect between legs' size and orientation ($p=.34$). These results, shown in Figure 19, are partially consistent with our previous findings and the literature (Mancini, Longo, Kammers, & Haggard, 2011; Romano et al., 2016;

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[6] This chapter is based on the paper by Tosi, G., Parmar, J., Dhillon, I., Maravita, A., &Iaria, G. Body illusion and affordances: the influence of body perception on space interaction (under review)

van der Hoort et al., 2011) and confirm that the Full-Body Illusion-like paradigm elicited the embodiment of the fake legs only during the experimental condition (i.e. Anatomical orientation) and not in the control one (i.e. Non-anatomical orientation). Furthermore, they show that the amount of embodiment generated by the normal-sized legs is significantly larger than that of the long legs; the latter is comparable to the that of the normal leg in non-anatomical posture.

The results obtained from each specific factor of the questionnaire are reported in Table 7 in the Appendix.

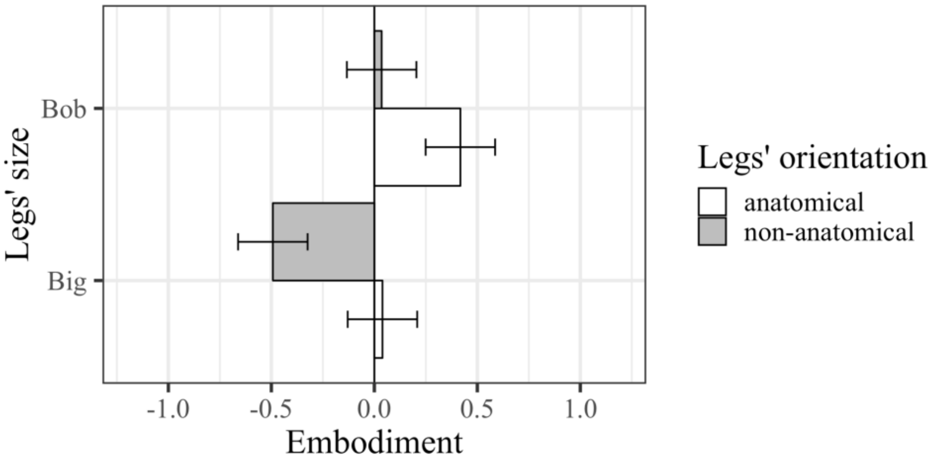

Figure 19. **Results of the two-way repeated measure ANOVA on the embodiment statements.** The columns show the ipsatized scores for each condition: standard size legs (upper part) and long size legs (lower part) in both anatomical (white columns) and non-anatomical (grey columns) orientations. The error bars show the confidence interval limits. The figure shows the significant main effects of size and orientation, with higher embodiment scores for the standard size as compared to the long one and in the anatomical orientation as compared to the non-anatomical one.

Imagery walking task

The Linear Mixed Model (LMM) three-way ANOVA, with the percentage of time misestimation as the dependent variable, revealed a significant main effect of Distance (F(3, 2533)= 115.32, p≤.001) with the misestimation increasing with longer distance (6m (CI: -11.06; 9.41); 12m (CI: -22.79; -2.32); 18m (CI: -31.88; -11.39); 24m (CI: -35.53; -15.04)). The analysis also revealed a significant main effect of Size (F(1,2533)= 16.68, p≤.001,) with a higher underestimation of the walking time after watching the long legs video (CI: -27.34; -6.87) as compared to the standard legs one (CI: -23.29; -2.80). Crucially, our hypothesis was verified by the significant interaction between Legs' Size and Legs' Orientation (F(1, 2533)= 7.12, p ≤.05), revealing that participants imagined walking faster after watching the video with the longer legs in an anatomical orientation (CI: -28.28; -7.82) as compared to the standard legs in the same position (CI: -21.51; -1.04). On the contrary, looking at the two control conditions with the legs in the video oriented in a non-anatomical orientation, we did not

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find such a difference between the standard (CI: -25.07; -4.55) and the long legs (CI: -26.40; -5.92) (see Figure 20).

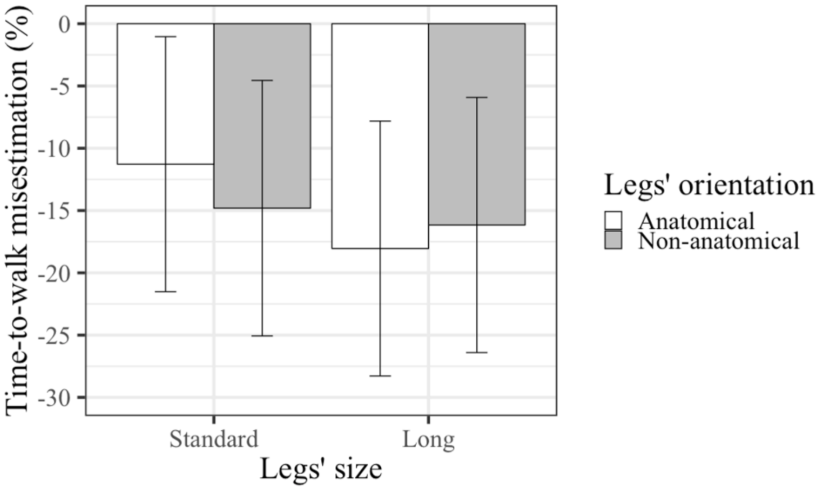

Figure 20. **Significant interaction between Size and Orientation**. The figure shows the significant interaction between Size and Orientation as a result of the Linear Mixed Model (LMM) three-way ANOVAs on the percentage of misestimation in the Imagery walking task. The columns show the percentage of misestimation in the standard legs (on the left) and long size legs (on the right) in both anatomical (white columns) and non-anatomical (grey columns) orientations. The error bars show the confidence interval limits. The result shows that participants imagined walking faster after watching the video with the longer legs as compared to the standard legs.

Moreover, we found a significant interaction between Legs' Size and Distance (F(3, 2533)= 2.94, p ≤.05) (see Figure 21), showing that, independently by the fake legs' posture, the difference emerged in the time-to-walk estimation between the Long and the Standard legs decreased with increasing distances (long legs-6 meters (CI: -15.25; 5.21); standard legs-6 meters (CI: -6.86; 13.62); long legs-12 meters (CI: -25.20; -4.73); standard legs-12 meters (CI: -20.39; -0.09); long legs-18 meters (CI: -33.34; -12.86); standard legs-18 meters (CI: -30.42; -9.92); long legs-24 meters (CI: -35.58; -15.10); standard legs-24 meters (CI: -35.49; -14.97)).

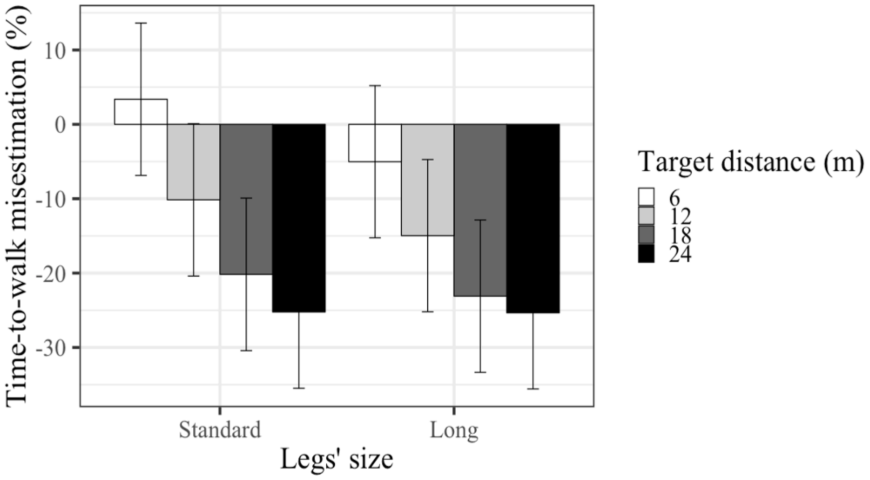

Figure 21. **Significant interaction between Size and Distance**. The figure shows the significant interaction between Size and Distance as a result of the Linear Mixed Model (LMM) three-way ANOVA on the percentage of misestimation in the

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Imagery walking task. The columns show the percentage of misestimation in the standard legs (on the left) and long size legs (on the right) for each target distance: 6m (white columns), 12m (light grey columns), 18m (dark grey columns), and 24m (black columns). The error bars show the confidence interval limits. The results show that the estimation difference between the Long and the Standard legs decreased with increasing distances of the target.

Finally, the Linear Mixed Model (LMM) one-way ANOVA with the walking time as the dependent variable, the environment (Real/Virtual) as fixed effect within-subject factor, and the participants as the clustering variable, revealed a main effect of Environment ($F(1,368)= 188.58$, $p\leq .001$) with shorter time-to-walk estimations in the virtual environment (CI: 7.26; 8.56) as compared to time-to-walk estimations in the real environment (CI:10.44;11.82). These results are in contrast with the findings by Plumert and collaborators (2005). It is our opinion that the main difference, as directly stated in the paper by Plumert (2005), is the support used for the virtual environment (large-screen immersive displays vs HMD). Indeed, the authors "displayed the virtual environment on three 10 ft × 8 ft-high screens placed forming a three-walled room. […] Three projectors were used to rear project high-resolution, textured graphics onto the screens (1280 × 1024 pixels on each screen), providing participants with 270° of non-stereoscopic immersive visual imagery". On the contrary, we used Head Mounted Displays and found an underestimation of time-to-walk in the virtual environment as compared to the real walking speed of each participant. Our results are consistent with previous findings reporting an underestimation of time-to-walk in a virtual environment using HMD (Loomis & Knapp, 2003; Swan, Jones, Kolstad, Livingston, & Smallman, 2007).

7.5. CONCLUSION

It is well-known that our body serves as a frame of reference in our interaction with the environment around us (Merleau-Ponty, 1945; van der Hoort et al., 2011). Here, we hypothesized that an altered representation of the body would affect how individuals perceive their interaction with the spatial surrounding. To test this hypothesis, we adopted a Full-Body Illusion-like paradigm to induce an altered perception of the individuals' legs' size (Fini et al., 2015; Proffitt et al., 1995, 2003), and asked participants to perform an imagery walking task in a virtual environment. First, we confirmed that the body illusion took place, as shown by the participants' subjective experience of embodiment. Then, we verified our hypothesis that the perceived length of the legs, as induced by the Full-Body Illusion-like paradigm, affected the performance of the participants during the imagery walking task. Our results showed that participants imagined walking faster after watching the video with the longer legs (as compared to the standard ones) when they saw the limbs in an anatomical orientation; on the contrary, this effect was not present in the control condition when both standard and long legs were turned 45°

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counter-clockwise. These findings provide evidence of a clear effect of the body illusion on the imagery walking task.

It has been proposed that the synchronous visuotactile stimulation during the body illusion produces a congruence between the visual input in the HMDs and the tactile perception on the subjects' body (Ehrsson, 2007; Keizer et al., 2016). This correspondence between two sources of information, together with the visual capture from the artificial legs would temporally modify proprioceptive inputs, leading to the illusionary embodiment of the fake legs (Pavani, Spence, & Driver, 2000; Tosi et al., 2018). Here, we suggest a more powerful influence of the visual capture on the imagery walking task. Even if subjects did not experience the ownership of the longer legs completely, it is possible that the visual input itself influenced the perception of body affordances during the imagery walking task, leading to an increase of walking time underestimation with the anatomical long legs. Such an influence could also explain the higher underestimation in the control conditions: the visual suggestion, that is part of the illusion, could have influenced the perception of body affordances during the non-anatomical conditions as well. Indeed, the overlap between embodiment and other implicit measures, such as the proprioceptive location of the body, is not always present in the literature (Maselli & Slater, 2014; Romano, Caffa, Hernandez-Arieta, Brugger, & Maravita, 2015), confirming that it is possible to induce the implicit misperception of the body without any conscious illusory experience of embodiment. Our results are in line with these findings and further suggest that imagined locomotion and subjective embodiment can be dissociated.

The findings reported in our study are also consistent with the evidence reported by van der Hoort and collaborators (2011) in which the experience of a small body induces the perception of objects to be farther away, and the experience of a bigger body induces the perception of the same objects to be nearer. Our study adds to these findings the new evidence related to the task performed by participants: while van der Hoort and collaborators (2011) asked for an explicit distance judgment, in our study participants were required to imagine walking from their position to the location where the target was displayed. We did not exclude that the results reflect an effect of distance instead of walking time because if objects appeared nearer to the participants, they would show a great misestimation in their time-to-walk. Nevertheless, since we did not ask for a distance judgment directly, we do not want to speculate about such an effect, and we discuss the results coherently with what was the aim of our task. We were not interested in explicit distance judgment, but in the indirect influence of distorted body representation on subjects' perception of their locomotion and interaction with the space around them. Our study suggests that body illusions could indeed affect the way we imagine our interaction with the spatial surrounding.

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Previous studies have already addressed the interaction between the body and the intention to act in the space around it (Fini et al., 2015; Proffitt et al., 1995, 2003). In fact, there is already evidence that the perceived affordances of the body affect the estimation of aperture widths (Stefanucci & Geuss, 2009; Warren & Whang, 1987), egocentric distance of objects (Proffitt et al., 2003), and geographical slant (Proffitt et al., 1995). Our study contributes to the understanding of the relationship between body and space by providing evidence that an experimentally altered body perception can significantly affect such imagined relationship. Interestingly, though, this relationship between body perception and space seems to fade with the temporal distance from the body illusion. Indeed, the difference emerged in the time-to-walk estimation between the Long and the Standard legs decreased with increasing length to be walked independently by the fake legs' posture. These findings suggest a timing effect: the more the subjects imagine walking, the more they rely on their actual body representation, while the embodiment effect gradually vanishes. Previous works confirmed that body representation could be modified by means of body illusions only temporarily (Gandevia & Phegan, 1999; Tosi et al., 2018); our results indicate the same temporal limit occurs in the context of an imagined interaction with the space.

Finally, our study shows that participants are more willing to accept, as part of their own body, external legs holding size and orientation coherent to their own legs. Indeed, participants provided largely positive embodiment ratings for the video with the standard legs presented from an anatomical viewpoint, nearly neutral for non-anatomical normally sized and anatomical longer size, and even negative ratings for the video with the long legs in a non-anatomical orientation. These results are partially in line with previous studies reporting the subjective effect of embodiment over body parts of different sizes (Mancini et al., 2011; Romano et al., 2016; van der Hoort et al., 2011). In our study, we did not find a significant embodiment of the long legs, even when they are presented from an anatomical viewpoint. This partial inconsistency with previous studies may be explained in light of two components of the body illusion: the manipulation of either the size or the orientation of the legs. In particular, it is possible that when both factors are coherent with the participant's body (i.e. when the legs have a standard size and are shown from an anatomical viewpoint), they induce a strong illusion of embodiment. This effect may be conveyed by the matching of different sources of information: on one hand by the proprioceptive and tactile signals coming from the body, and on the other hand by the visual input of the videos. On the contrary, when neither the size nor the orientation of the fake legs matches the body of the subjects (i.e. long size legs presented in a non-anatomical orientation), they recognize the visual input as not being part of their body. As for the other conditions (standard size in non-anatomical orientation and long size in anatomical orientation), only one of the factors is coherent

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with the stored body representation. The illusion elicited a conflicting situation in which participants cannot distinguish if the legs presented in the video are part of their body, reflecting the embodiment scores that appeared to be around zero. This novel approach to the understanding of body illusions takes into account a gradient of the embodiment experience instead of a dyadic distinction "embodied vs non-embodied". This hypothesis seems to fit well also with a study by Tieri and collaborators (2015) that found that observation of limb discontinuity can modulate ownership over a virtual body observed from a first-person perspective. In this case as well, the discontinuity or the partial occlusion of an anatomically plausible body part elicited a conflicting situation and lower the level of embodiment.

The main limitation of the present study is the weak embodiment effect emerged after the video with the long legs, which seems to diverge from the results of the imagery walking task and from previous studies (Mancini et al., 2011; Romano et al., 2016; van der Hoort et al., 2011). Moreover, we did not assess the actual interaction with the environment; on the contrary, we used an imagery task. We modified this assessment from previous studies about distance perception, which confirmed that subjects take a similar time to actually walk and imagine themselves walking (Decety et al., 1989; Plumert et al., 2005). Since embodiment effects are based on proprioceptive and somatosensory inputs, we chose imagery walking to limit additional signals coming from the body. In fact, proprioceptive and vestibular inputs elicited by a real walking task, such as tactile information coming from the feet and vestibular information triggered by actual locomotion could have introduced confounding factors and limited the effect of the illusion. On the contrary, we preferred to focus our investigation on subjects' perception of the way they imagine interacting with the space, avoiding any external non-visual interference. Future studies should investigate body illusions effects on actual interaction with space.

In conclusion, the present study contributes to a better understanding of the relationship between our body and the surrounding, suggesting an influence of body metric on the way we perceive our interaction with the environment around us. These findings could be particularly meaningful in the development of intervention for those individuals suffering from an impairment of body perception due to hemiplegia or phantom limb (Dohle et al., 2009; Flor et al., 2006; Hallett, 2001; Tosi et al., 2018). In the field of cognitive impairment, there is a growing attention to the non-pharmacological management of this disease (Zucchella, Sinforiani, & Tamburin, 2018). One of the key points is the role the designed and built environment plays in supporting individuals living with a disease (Barrett, Sharma, & Zeisel, 2019; Calkins, 2018). For instance, Barrett and colleagues (2019) suggested that designing an environment following the principles of (a) manageable cognitive load, (b) clear sequencing and (c) appropriate level of stimulation could improve the quality of life of the individuals suffering from dementia. Our findings suggest that an altered body representation could impact our

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perception of the space providing new insights for non-pharmacological management of body perception impairment. Designing environments that takes into account also physical and motor impairments could be supportive and prosthetic for the perception that individuals have of their interaction with the surroundings.

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8. EXPERIMENT 7. HOW AN ILLUSORY BODY DISTORTION CAN AFFECT DISTANCE PERCEPTION IN EXTRA-PERSONAL SPACE

8.1. INTRODUCTION

In the present work we will use the same Full-Body Illusion-like paradigm in order to modify the perception of body metric, with the purpose to investigate the relationship between body size and extra-personal space size. We know that the body works as a fundamental reference in peri-personal space processing (Holmes & Spence, 2004), our hypothesis is that a manipulation of body size could influence the perception of distance between landmarks in far space. In particular, body illusions can induce perceptual delusion of embodying other bodies with different sizes. The manipulation of body representation, as induced by a body illusion, can affect the perception of distances in extra-personal space.

8.2. MATERIALS AND METHODS

8.2.1. Participants

We recruited 24 healthy volunteers (14 females, mean age 22.71±1.90 years, range 18-26 years; mean education 14.71±2.35 years, range 8-16 years) through the Research Participation (SONA) System of the Psychology Department of the University of Milano - Bicocca. In order to calculate the a priori sample size of participants to be included in the study, we conducted a power analysis with G*power 3.1.9.2. The analysis revealed that in order to obtain a power of 0.80, with alpha set at .05, and effect size at 0.25, we needed to test a total of 24 participants. The study was approved by the local Ethics Committee "Commissione per la Valutazione della Ricerca, Dipartimento di Psicologia" of the University of Milano-Bicocca and was conducted by the ethical standards of the Declaration of Helsinki (World Medical Organization, 1996). Informed consent was obtained from all individual participants included in the study.

The experimenter explained to the participants the general aim of the study and the procedure before collecting the informed consent. At the end of the experimental sessions, the experimenter also described the specific scope of the experiment.

8.2.2. Procedure

Participants underwent two testing sessions in two different days, with a washout week. At the beginning of the first session, participants performed a space distance task. We collected this data as a baseline measure, to control for the individuals' natural variability in distance estimation.

In each testing session, participants were exposed to a body illusion with different body sizes and were required to perform the same space distance task, in order to investigate the potential influence of the body illusion on distance perception in extra-personal space. After each condition, we also administered an embodiment questionnaire to evaluate the subjective experience of embodiment during the body illusion. Finally, we recorded the number of steps needed to walk through a distance of five meters.

Body Illusion

Participants sat in an armchair, keeping their arms behind the back of the chair. During the procedure participants wore a set of Head-Mounted Displays (HMDs – Samsung Gear VR 2016, Samsung Electronics, field of view = 101°) in which they saw the same pre-recorded videos as in Experiment 6. During the experiment, participants were invited to look down at their legs and lower abdomen to increase the focus on the fake body.

The procedure and the conditions were maintained from Experiment 6 (see Figure 18). By crossing the variables size and viewpoint, we obtained four different conditions: Standard-anatomical; Standard-non-anatomical; Big-anatomical; Big-non-anatomical. We administered the Standard and Long conditions, in a counterbalanced order, in two different testing sessions, with one washout week.

Space Distance Task (SDT)

At the beginning of the procedure and after each condition of the body illusion, participants underwent a space distance task. For this task, we selected a well-known environment, the square facing the main entrance of the University of Milano-Bicocca, with four environmental landmarks (maple trees), as shown in Figure 22, panel a. Participants were presented a 360° picture of the same environment on a first-person perspective (Figure 22, panel b). Pictures were taken with a 360° camera (Samsung Gear 360 2017 - features: CMOS 8.4MP x2/F2.2 lens; resolution: 360˚ Dual Lens: up to 4096 x 2048, 15 megapixel) from the very exact position of the participant's viewpoint, providing an immersive, realistic and ecological context so that it was possible for the participant to visually explore the environment.

On each trial, two landmarks appeared to be highlighted (Figure 22, panel c), and participants were asked to verbally estimate the distance between them. For each pair of landmarks, we asked participants to evaluate the distance in meter and to indicate the number of steps they would need to walk from one landmark to the other. There were four possible landmarks, and six possible stimulus pairs. Each pair was presented four times for a total of 24 stimulus pairs.

SDT - responses in meters. We processed the responses provided in meters following two different procedures. On the one hand, we applied the Multidimensional Scaling and the Procrustes Alignment that provide a global index of shape dissimilarity; on the other hand, we calculated the percentage of error estimation for each stimuli pair, called Misestimation (see chapter 3.2.2).

We calculated both the Procrustes Distances and the Misestimation for the baseline and each condition considering the size (standard/long) and the orientation (anatomical/non-anatomical) of the legs presented during the body illusion. Procrustes distances were log transformed to improve the fit with normal distribution for the inferential statistic.

SDT - responses in steps. Thanks to the assessment of the number of steps needed to walk a distance of five meters, which we administer at the end of the entire procedure, we computed the number of steps that participants really needed to walk from each landmark to the other ones. Finally, we calculated the percentage of misestimation for each pair of landmarks in the baseline and in each condition considering the size (standard/long) and the orientation (anatomical/non-anatomical) of the legs presented during the body illusion.

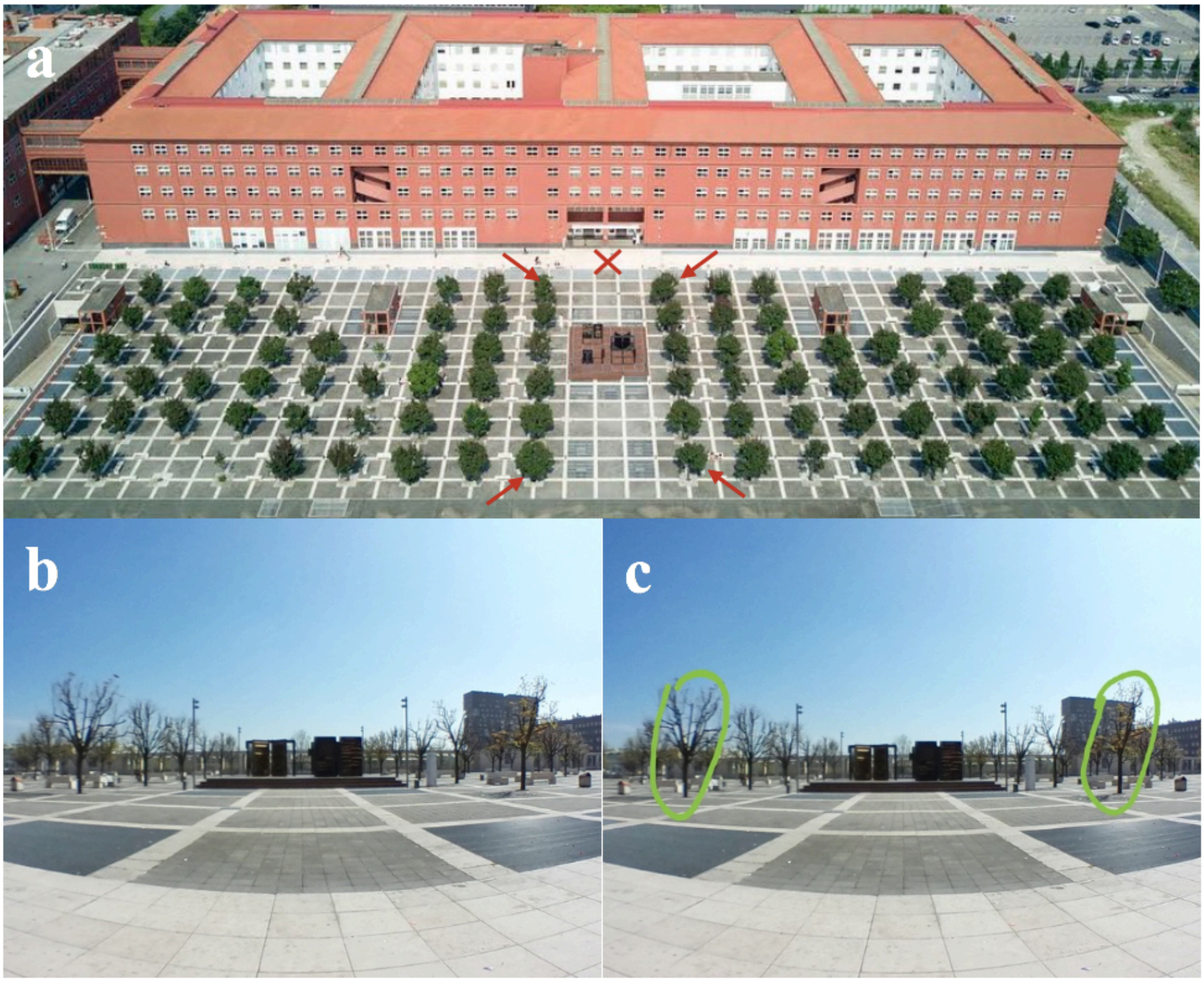

Figure 22. **Space distance task. Panel a:** the picture shows the well-known space and the environmental landmarks selected for the task (the four trees indicated by a red arrow); the X shows the participants' viewpoint. **Panel b:** the picture shows the 360° picture of the same environment from the participants' viewpoint. Panel c: the picture shows one of the trials of the Space Distance Task, we asked participants to evaluate the distance between the two stimuli highlighted.

Embodiment

At the end of each condition, we evaluated the embodiment of the artificial legs presented in the videos with same questionnaire adopted for Experiment 1 and 3. Data were processed following the same steps, namely the scores were ipsatized and then aggregated to obtain an embodiment score averaging the items: Q1, Q2, Q3, Q4 (reversed), Q5, and Q6. The full questionnaire is reported in Appendix, Table 1.

We expected to replicate our previous results, i.e. to find significant effects of both Size and Orientation factors.

8.3. ANALYSIS

We conducted the analyses with R 3.4.2 (R Development Core Team 2008), JASP 0.8.4 (Jasp Team, 2017), and Jamovi 1.0.5 (The Jamovi project (2019)). More specifically to run MDS we used the packages *stats* (*cmdscale* function), Procrustes Distance have been calculated with the package *vegan* (function *procrustes*). Misestimation percentage were calculated with an *ad hoc* formula in R.

Embodiment questionnaire

We ran a within-subjects 2(Size) * 2(Orientation) repeated measure ANOVA on the ipsatized responses for the embodiment factor. Significant effects were interpreted inspecting 95% Confidence Intervals.

SDT - Global shape dissimilarities

Procrustes Distance ranges between zero (i.e., the two configurations have the same shape), and one (i.e., the two configurations do not share spatial structure at all). We first analysed the Procrustes Distances by checking for significant differences from zero, to assess if there is any distortion in the perceived configuration of points. To do so, we ran a series of independent one-sample t-tests on the Procrustes Distances of each condition. Then, in order to assess any influence of the body illusion on the SDT, we ran a within-subjects 2(Size) * 2(Orientation) repeated measure ANOVA with the baseline as a covariate variable. Significant effects were interpreted inspecting 95% Confidence Intervals.

SDT - Misestimation

We analysed the responses given both in meters and in steps with the same models. We conducted a Linear Mixed Model (LMM) one-way ANOVA with the misestimation as the dependent variable and the order of presentation of the conditions (baseline / condition1 / condition2 / condition3 / condition4) as both fixed and random effects. We set participants as clustering variable. Significant effects were interpreted inspecting 95% Confidence Intervals. With this analysis we wanted to assess any practice effect on the SDT. Moreover, in order to assess any influence of the body illusion on the SDT, we ran an LMM three-way ANOVA with the misestimation as the dependent variable. Fixed effects were Size (standard/long) and Orientation (anatomical/non-anatomical) as within-subject factors, and Baseline as covariate. We set participants as clustering variable. Significant effects were interpreted inspecting 95% Confidence Intervals.

8.4. RESULTS

Embodiment questionnaire

The 2(Size) * 2(Orientation) repeated measure ANOVA resulted in significant main effects of Orientation (F(1,23)= 16.47, p≤ .001, $\eta 2$= .42). Both the standard legs (CI: 0.34; 0.64) and the long ones (CI: 0.30; 0.66) presented in an anatomical orientation induced a stronger embodiment as compared to the non-anatomical orientation (standard legs (CI: -0.12; 0.31), long legs (CI: -0.26; 0.21)), as shown in Figure 23.

The results obtained from each specific factor of the questionnaire are reported in Table 8 in the Appendix.

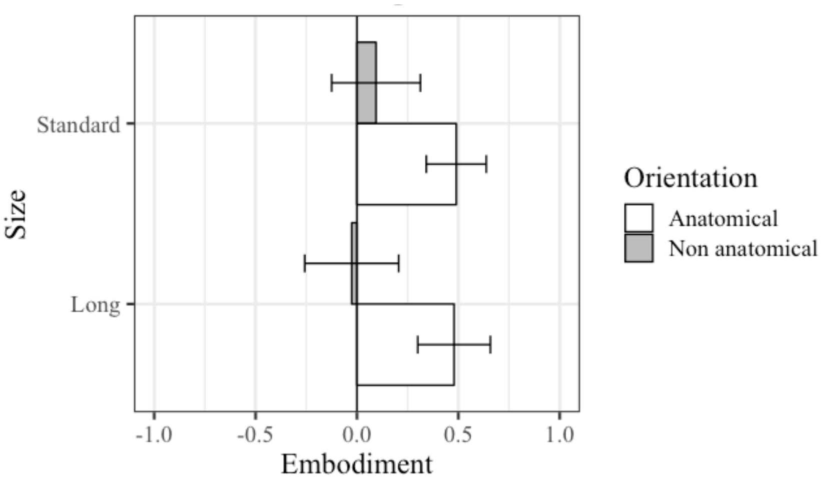

Figure 23. **Embodiment questionnaire results**. The figure shows the results of the within-subjects 2 (Size) x 2 (Orientation) repeated measure ANOVA on the averaged ipsatized answers to embodiment statements. Grey and white columns display Non-anatomical and Anatomical conditions respectively. Error bars display 95% confidence interval limits.

SDT - Global shape dissimilarities

The one-sample t-tests were significant for all the conditions (see Table 7). These results suggested that the perceived grid significantly differed from the actual grid of the targets in all conditions (Figure 24).

	t	df	p	mean difference	95% ci lower	95% ci upper
Baseline	-9.923	23	< .001	-0.648	-0.783	-0.513
Long anatomical	-7.989	23	< .001	-0.723	-0.910	-0.536
Long non-anatomical	-8.771	23	< .001	-0.789	-0.975	-0.603
Standard anatomical	-17.290	23	< .001	-0.891	-0.997	-0.784
Standard non-anatomical	-13.198	23	< .001	-0.871	-1.008	-0.735

Table 7. Results of the independent one-sample t-tests ran on the Procrustes Distance for each condition.

Nevertheless, the 2(Size) * 2(Orientation) rmANOVA did not result in any significant effect (all p-values ≥ 0.14), discarding the possibility that the body illusion influences the perception of the global configuration of landmarks in far space.

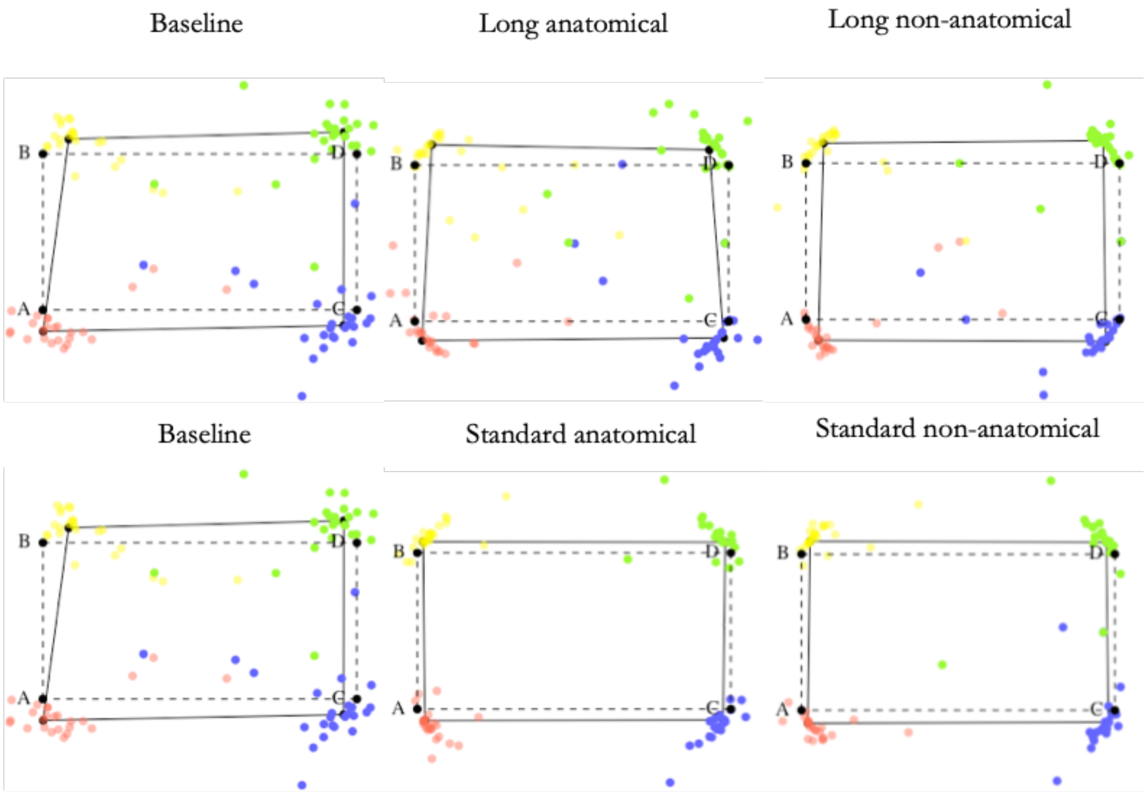

Figure 24. **Example of the Multidimensional Scaling for the different conditions**. The solid grid represents the mean of the subjects' perceptive responses compared with the actual grid (dashed). We characterized with different colours the perceived location of each point by each participant.

SDT – Misestimation:

For both the responses in meters and in steps, LMM one-way ANOVA did not result in any significant effect (response in meters: p-value= 0.674; response in steps: p= 0.824), rejecting the possibility of a practice effect on the SDT.

The LMM three-way ANOVA ran on the response in meters revealed a significant main effect of Size (F(1,2235)= 73.76, p ≤.001). The estimation made after the videos with the long legs were more precise (CI: -76.2; 73.9) rather than after the videos with the standard legs (CI: -43.8; 106.2). We also found an interaction between the legs size and the baseline (F(1,2235)= 616.69, p≤ .001).

Regarding the estimation of the number of steps, the LMM three-way ANOVA revealed a significant main effect of Size (F(1,2081)= 44.20, p≤.001). However, in this case, we found an overall overestimation of the number of steps needed to cover the distance. Moreover, the estimation made after the videos with the standard legs were more precise (CI: -82.8; 120) rather than after the videos with the long legs (CI: -56.0; 147). We also found an interaction between Size and the covariate

Baseline (F(1,2081)= 690.90, p≤.001), and an interaction between Orientation and the covariate Baseline (F(1,2081)= 13.26, p≤.001). Crucially, we also found a significant three-way interaction between Size, Orientation and the covariate Baseline (F(1,2081)= 17.04, p≤.001), as shown in Figure 25. Such results suggest that, following the videos with the standard legs, independently of their orientation, the lower is the performances of the participants at baseline, the higher is the underestimation after the body illusion. The opposite pattern emerged in the case of the long legs: the lower is the performances of the participants at the baseline, the higher the overestimation after the body illusion. Moreover, this effect is more evident when the legs are presented from an anatomical point of view, then in the control condition.

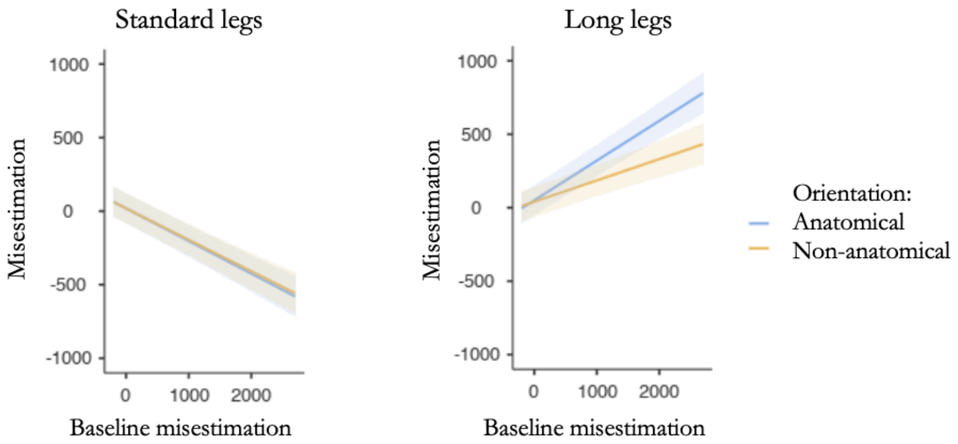

Figure 25. **Three-way interaction between Size, Orientation and the covariate Baseline.** After the videos with the standard legs, independently by their orientation, the lower is the performances of the participants at the baseline, the higher is the underestimation after the body illusion. The opposite pattern emerged in the case of the long legs: the lower is the performances of the participants at the baseline, the higher is the overestimation after the body illusion.

8.5. CONCLUSION

We know that our own body serves as a fundamental reference in visuo-perception tasks in the space surrounding us (van der Hoort et al., 2011). In the past few years many studies have focused on the relationship between body representations and peri-personal space (Holmes & Spence, 2004; Longo & Lourenco, 2006; Linkenauger, Ramenzoni, & Proffitt, 2010) defined as the space immediately surrounding our bodies (Rizzolatti et al. 1997). Nevertheless, it isn't clear if the representations of the body could influence our perception of "far space" or extra-personal space (EPS).

In the present work we used a Full-Body Illusion-like paradigm in order to modify the perception of body metric, with the purpose to investigate the relationship between body size and the perception of extra-personal space size. Our hypothesis was that a manipulation of body size could influence the perception of distance between landmarks in far space.

We first evaluated the subjective experience of embodiment after the videos with different body sizes. Both the standard legs and the long ones presented in an anatomical orientation induced a stronger embodiment as compared to the non-anatomical orientation. These results are consistent with previous studies (Mancini, Longo, Kammers, & Haggard, 2011; Romano et al., 2016; van der Hoort et al., 2011) and confirm that it is possible to induce the embodiment of a fake body when it is presented from a first-person perspective and in an anatomical position. In particular, we induced illusory ownership over fake legs holding both realistic size and unrealistic bigger size.

In order to assess the perception of distances in far space, we used a space distance task modified from previous studies on body perception (Longo, 2015; Longo & Morcom, 2016). We presented a 360° picture of a well-known environment with four environmental landmarks (i.e. trees) from a first-person perspective. On each trial, two landmarks appeared to be highlighted and participants were asked to verbally estimate the distance in meters between them and to indicate the number of steps they would have needed to walk from one landmark to the other one.

We first collected a baseline measure, to control for the individuals' natural variability in distance estimation. For both the response in meters and steps, the results did not show in any significant effect of time rejecting the possibility of a practice effect on the SDT. Although, we used the baseline as a covariate measure for each subsequent analysis, so to consider the natural ability in judging distances.

In order to evaluate any possible influence of the body illusion over the global perception of the space, we calculated, for each condition, the Procrustes Distance (PD). The results suggested that the perceived grid significantly differed from the actual grid of the targets in all conditions. Previous works strongly supported the idea that humans have a distorted map of the body to perceive tactile events (Longo et al., 2015; Longo & Morcom, 2016; Stone et al., 2018). In a similar way, our participants perceived the global configuration of the space presented through the HMDs distorted as compared to the real disposition of the natural landmarks. Nevertheless, the rmANOVA did not result in any significant effect, discarding the possibility that the body illusion influences the perception of the global configuration of landmarks in far space. Even if the grids resulted to be distorted in each condition, our data did not confirm a relationship between the body illusion administered before it and this distortion.

Misestimation additionally measures length judgment errors, independently of the shape of the grid, and it represents a complementary index to the Procrustes Distance. For this reason, we computed the percentage of misestimation for both the responses in meters and in number of steps. The LMM three-way ANOVA ran on the response in meters revealed a significant main effect of Size and an interaction between the legs' size and the baseline. These results suggest that partializing the baseline ability of each participant, the estimations made after the videos with the long legs were more precise rather than after the videos with the standard legs. Indeed, in these conditions, our participants overestimated the distance between the target pairs of trees. However, when we take into account the baseline abilities, we found that the higher the overestimation at the beginning of the procedure, the higher the overestimation after the videos with the standard legs, and the underestimation after the videos with the long legs. It is possible that the body illusion affects the most those subjects showing lower performances in judging distances. This interaction confirmed that being exposed to a video with a standard pair of legs enhances the overestimation of allocentric distances. This result is in line with a study by Fini, Brass & Committeri (2014) revealing that target object are judged as farther when the reference frame is an object as compared to a human agent with movement potentialities. Both studies show an overestimation of allocentric distances between objects in far space. Regarding the video with the long legs, we proposed a visual influence independent by the orientation of the legs and their embodiment. Seeing longer legs during a body illusion reduced the perceived distance between points in far space thanks to the visual capture; i.e. the higher influence of visual inputs over proprioception and tactile sensation (Pavani et al., 2000; Romano, Bottini, et al., 2013; Tosi et al., 2018). This finding is consistent with the evidence reported by van der Hoort and collaborators (2011) in which the experience of a bigger body induces the perception of objects to be nearer as compared to a normal size body. This compression of distances after a body illusion with longer legs seems to be stable for both egocentric (van der Hoort et al., 2011) and allocentric distances. In line this hypothesis, a study by Nori, Iachini & Giusberti (2004) whose results showed no difference between subject-to-object and object-to-object localization.

Interestingly, we found a significant effect of Size and a significant interaction with the baseline for the number of steps as well. However, in this case, partializing the baseline ability of each participant, we found an overestimation in both conditions but a higher precision after the video with the standard legs. When we take into account the baseline abilities, we found that the higher is the overestimation of steps at the beginning of the procedure, the higher the overestimation after the videos with the long legs, and the underestimation after the videos with the standard legs. Crucially, we also found a significant three-way interaction between Size, Orientation and the covariate Baseline. The results suggested that after the videos with the standard legs, independently of their orientation, the higher the overestimation of needed steps at baseline, the higher the underestimation after the body illusion. Following the previous interpretation, we suggest that the body illusion affects mostly those subjects showing lower performances during the baseline task. In this case, being exposed to a video with a standard pair of legs reduces the perception of the steps needed to walk between two points in far space. Both in the case of embodied anatomical legs and non-embodied non-anatomical legs, participants use a standard size pair of legs as a reference in evaluating the number of steps needed to walk a certain distance. The opposite pattern emerged in the case of the long legs: the higher is the overestimation of judged steps at the baseline, the higher is the overestimation after the body illusion. These results are in contrast with what reported by Van der Hoort and colleagues (2011). They used a similar body illusion paradigm and asked participants to perform a blind walking task. The direct comparison between big and small bodies revealed that participants walked shorter distance after the illusion with the big body, confirming their previous results of underestimation of distances. Our studies are not directly comparable, though. Van der Hoort and colleagues (2011) presented the target from a first-person perspective asking for egocentric distance estimation. On the contrary, we asked for an estimation of the number of steps needed to walk between two landmarks in extra-personal space: this task required judging allocentric distances in far space. If egocentric coordinates define the spatial representations underlying both subject-to-object and object-to-object localization in space, as suggested by Nori, Iachini, & Giusberti (2004) the difference has to be found in the different task (verbally reporting the number of steps vs blind walking). Moreover, van der Hoort (2011) compared the big body with the small one, while we compared the long legs with a standard size pair. However, in line with the study by van der Hoort and colleagues (2011), the revealed effect is more evident during the experimental condition (in our case, when the legs are presented from an anatomical point of view), than in the control one. When the legs are embodied (anatomical condition) the size of the legs influences the most the estimation of the number of steps. We suggest that the lack of experience with such long legs, enhance the number of steps that participants imagined they would have needed to walk between the landmarks.

The opposite pattern emerged for the judgments made in meters and steps could be due to an attempt to correct the estimation. A limitation of our procedure was that we always asked for the distance in meters before the steps needed to walk that distance. Our hypothesis is that the misestimation of the number of steps is an attempt to counterbalance the error previously done with the distance in meters, going into the opposite direction.

In conclusion, the present study confirms that it is possible to induce the embodiment of a fake body holding either standard or longer legs when it is presented from a first-person perspective and in an anatomical position. Moreover, the illusory ownership of different sizes of legs, affects the perception of allocentric distances to different extents. The visual capture of the illusion seems to influence both the estimations of distances in meters and number of steps. On the one hand, the embodiment of longer legs reduced the perceived distance in meters, on the other hand, the embodiment of the same legs produces an enhancement of the number of steps participants imagined they would have needed to walk between the same landmarks. These results emerged considering the baseline abilities of each participants to estimate allocentric distances in far space both in meters and in steps.

As for our knowledge this is the first experiment studying the relationship between modified body metrics and allocentric distance perception in extra-personal space.

9. GENERAL DISCUSSION

In daily life experience we continuously receive sensory input from both the body and the world around us, that the brain integrates to create comprehensive, supra-modal and coherent mental representations of our own body (Berti, 2013).

Many different accounts have been proposed to illustrate such a complex representation, as illustrated in the introductory part of the present work. In particular, the brain holds a precise description of the body size and shape, also named body model (Longo et al., 2010; Tamè et al. 2019).

Recently, there has been a growing interest in the characterisation of the body model in healthy subjects and patients suffering from body representation disorder. In particular, two tasks have been employed to this aim: the forearm bisection task (Bolognini et al., 2012; Garbarini et al., 2015; Sposito et al., 2010; Sposito et al., 2012), and the Tactile Distance Task (Longo, Mancini, & Haggard, 2015; Longo & Morcom, 2016; Sadibolova, Tamè, Walsh, & Longo, 2018; Stone et al., 2018). Both suggest that the stored representation of our body size and length is distorted (Bolognini et al., 2012; Garbarini et al., 2015; Longo, Mancini, & Haggard, 2015; Longo & Morcom, 2016; Sadibolova, Tamè, Walsh, & Longo, 2018; Sposito et al., 2010; Sposito et al., 2012; Stone et al., 2018). In particular, the Tactile Distance Task revealed a general inclination to underestimate tactile distances in the longitudinal (proximo-distal) direction (Green, 1982; Longo, Mancini, & Haggard, 2015; Longo & Morcom, 2016; Sadibolova, Tamè, Walsh, & Longo, 2018; Stone et al., 2018), possibly due to the anisotropy of tactile receptive fields on the hand, being larger along the proximo-distal axis and shorter along the medio-lateral one (Longo and Haggard, 2011).

Crucially to the present work, we know that body representation is plastic: it can stably change according to life experience (Flor, Nikolajsen, & Jensen, 2006; Sposito, Bolognini, Vallar, & Maravita, 2012) as well as be temporarily altered by means of experimental protocols (Gandevia & Phegan, 1999; Giurgola, Pisoni, Maravita, Vallar, & Bolognini, 2019; Tosi, Romano, & Maravita, 2018). Indeed, in the past few years, several studies have adopted different experimental procedures to manipulate body representation, usually referred to as body illusions (H. H. H. Ehrsson et al., 2005; Medina et al., 2015; Pasqualotto & Proulx, 2015; Romano, Bottini, et al., 2013; Sanchez-Vives et al., 2010; Scandola et al., 2014; Tosi et al., 2018) whereby the brain is tricked towards including an alien body part (a rubber hand, an avatar, etc.) into the construction of the bodily self. The core mechanism accounting for the efficacy of these experimental procedures seems to be the process of embodiment, which can be defined as the experience of some properties of an object (in this case an alien body or body part) as part one's own body (de Vignemont, 2011). The experience of embodiment is typically assessed through physiological responses, such as the Skin Conductance Response (SCR), likely capturing more automatic aspects of embodiment signalled by arousal/affective states or through self-report questionnaires referring to the subjective sensations of ownership, agency and location of the external objects (Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008; Romano, Llobera, & Blanke, 2016; van der Hoort, Guterstam, & Ehrsson, 2011).

However, besides such automatic and subjective clues to embodiment, it remains unclear whether embodiment-based bodily illusion may impact even in the core representation of the metric of one's own body, i.e. the realistic estimation of the size of one's own body part. The focus of the present work is to understand whether the stable, albeit distorted, metric map of the body can be modulated through bodily illusions, or whether it is so profoundly grounded in mental representation that it cannot be altered by the temporary, illusory perturbation of body representation.

To this purpose, we used the Mirror Box Illusion together with the Forearm Bisection Task, in order to evaluate the metric perception of body parts in two cohorts of brain-damaged patients. Moreover, we used the Full-Body Illusion and the to induce a manipulation of the metric representation of the legs in healthy participants and the Body Distance task to understand the impact of the manipulation on body representation and body/space motor interaction. Moreover, since a proper body perception is critical for efficient interaction between individuals and spatial surroundings, our research focused on the specific influence of body metric representation on the estimation of the metric of extra-personal space. We hypothesised that the process of embodiment could shape our perception of the body metric, also influencing space representation.

The first step (Experiment 1) was to test the feasibility and the replicability of a Full-Body Illusion-like (FBI) paradigm for bodies of different sizes, controlling for the role of visual perspective in the illusory embodiment. We confirmed our expectations, inducing a stronger embodiment presenting fake legs from an anatomical perspective than from a non-anatomical one. Moreover, we obtained comparable embodiment scores with the big and the standard legs which were both more embodied than the small ones. We proposed that the congruency between vision, touch and proprioception, together with the visual capture of tactile information from the 360° videos overwrote proprioceptive and somatosensory information, resulting into the embodiment of the fake legs (Botvinick and Cohen 1998; Pavani, Spence, & Driver, 2000; Romano et al., 2013b). On the contrary, when the body was presented turned 45° counterclockwise, the incongruence between participants' position and the non-anatomical rotation of the legs prevented the embodiment even in the presence of synchronous visuotactile stimulation. These results are in line with the previous literature of embodiment of body parts with different sizes (Mancini et al., 2011; Romano et al., 2016a; van der Hoort et al., 2011) and suggested that we are more prone to incorporate standard size or bigger bodies, than smaller ones, accounting for a top-down influence on the embodiment (Pavani & Zampini, 2007).

Crucially to the project, we did not find any effect of session, suggesting that the FBI with our setup is replicable in the same participants more than once at the level of subjective experience.

Since we wanted to assess the impact of embodiment on the metric representation of one's own body, we run a methodological experiment (Experiment 2) to consolidate and validate the tactile distance estimation procedure on the leg (Body Distance Task – BDT). Our results strongly support the idea that humans have a distorted map of the body to perceive tactile events (Longo et al., 2015; Longo & Morcom, 2016; Stone et al., 2018) which is resistant to contextual experimental effects. Notably, previous studies have found a stretch along the medio-lateral (transversal) axis, and an equivalent compression of the proximo-distal (longitudinal) one (Longo & Haggard, 2011; Longo et al., 2015; Longo & Morcom, 2016; Stone et al., 2018). Coherently, we found higher underestimation on the proximo-distal axis than on the medio-lateral one. Regardless of the response method, subjects perceived a general reduction of the leg sizes, and, in particular, a contraction of the leg length, in line with the literature (Longo & Haggard, 2011; Longo et al., 2015; Longo & Morcom, 2016; Stone et al., 2018).

In Experiment 3, we replicated the FBI with different body sizes accompanying the questionnaire to the Body Distance Task (BDT). Our findings suggest that the vision of one's body can impact its metric representation, and, crucially to our purposes, this can be modulated by the seen size of the to-be-embodied body part. In particular, we found an underestimation of distances running along the proximo-distal axis as compared to the medio-lateral one only for the anatomical standard legs but not for the bigger one. We hypothesise that after embodying the bigger legs, our participants perceived their limbs longer as compared with the other illusory conditions. In the following two experiments we looked for the same kind of enlargement of the metric perception of the body, in two cohorts of patients, which showed impairments of body representation to different extents.

In experiments 4, we use the Mirror Box (MB) for contrasting the effects of negative plasticity. All patients showed a proximal deviation of the subjective midpoint at baseline of about 17% suggesting that the arm is implicitly represented shorter than it is. This result is in contrast with previous experiments using a similar task in healthy participants, where the baseline deviation was about 3% toward the hand (Sposito et al., 2012). This observation goes hand in hand with the contraction of cortical representation of affected limbs, occurring after brain lesion (Dohle et al., 2009). Following MB training, the subjective midpoint shifted toward the actual midpoint, as if the arm was perceived longer than just before the training. This central finding suggested that even a single training session with MB can improve body metric representation in hemiplegic patients. In line with our working hypothesis the MB may have realigned the visual feedback with the patient's intention-to-move the affected limb, promoting the embodiment of the mirrored healthy arm. This procedure may have partially compensated the distortion of body representation induced by the motor impairment. In hemiplegic patients, the non-use of the affected limb leads to what has been called "learned paralysis" (Taub et al., 1998). This additional deficit has been proposed to be grounded on the progressive reduction of the cortical representation of that underused body part representing a form of maladaptive plasticity (Dohle et al., 2009).

In experiment 5 we extended the study of motor representation through embodiment in patients with Ideomotor Apraxia (IMA) with heuristic and rehabilitative purposes. In these patients, a robust theoretical framework for its understanding suggests that it may originate from impaired access to body representation (Buxbaum, Giovannetti, & Libon, 2000; Canzano et al., 2016; Georg Goldenberg, 1995). We found that a single week of mirror box training where correct movement performed by the examiner were reflected in the mirror and imitated by the patient's hand hidden inside the box, significantly improves IMA as compared to one week of rehabilitation following frontal imitation. It is plausible to think that the embodiment of the experimenter's hand, performing correct movements, would improve the altered representation of the affected hand, thus improving its movements. Moreover, through the arm bisection task, we observed that the arm was bisected significantly closer to the objective midpoint after the experimental manipulation, suggesting an effect of the MB in modulating body metric perception in these patients. Our results support the idea that the vision of the anatomical hand in the mirror is embodied (Romano, Bottini, et al., 2013; Rossetti et al., 2019), thus positively impacting body representation, in line with what found with patients with hemiplegia (Tosi et al., 2018; Zampini, Moro, & Aglioti, 2004).

In Experiment 6, we used the same FBI paradigm to modify the perception of body metric, with the purpose to investigate the relationship between body size and body affordances. Previous work has witnessed strong relationship between body and the intention to perform actions in far space (Fini, Brass, & Committeri, 2015; Proffitt, Bhalla, Gossweiler, & Midgett, 1995; Proffitt, Stefanucci, Banton, & Epstein, 2003; Warren & Whang, 1987).

Our results showed that participants imagined walking faster after watching the video with the longer legs (as compared to the standard ones) when they saw the limbs in an anatomical orientation; on the contrary, this effect was not present in the control condition when both standard and long legs were turned 45° counter-clockwise. Nevertheless, this is the only experiment where we did not find a significant embodiment of the longer legs, even when they are presented from an anatomical viewpoint. We explained this partial inconsistency with previous results suggesting a novel approach to the understanding of body illusions, that takes into account a gradient of the embodiment experience instead of a dyadic distinction "embodied vs non-embodied". We proposed that only when both size and orientation of the fake legs are coherent with the participant's body, they systematically induce a strong illusion of embodiment. On the contrary, when neither the size nor the orientation of the fake legs match that of the participant's body, no embodiment is elicited. When only one of the factors is coherent with the stored body representation, the illusion elicited is inconsistent, and can be absent. This understanding of FBI seems to fit with the general findings of all the experiments presented here and may account for the unexpected embodiment of longer legs in anatomical posture found in this experiment.

Overall, the findings of this experiment provided evidence of an effect of the body illusion on the imagery walking task and suggested that imagined locomotion and subjective embodiment can be dissociated (Maselli & Slater, 2014; Romano, Caffa, Hernandez-Arieta, Brugger, & Maravita, 2015).

Interestingly, the relationship between body perception and space seems to fade with the temporal distance from the body illusion, since the difference found in the time-to-walk estimation between the long and the standard legs decreased with increasing length to be walked. These finding suggest a timing effect in the weighting of sensory signals: the more the subjects imagine walking, the more they rely on their actual body representation, while the embodiment effect gradually vanishes. Our study suggests that body illusions could indeed affect the way we imagine our interaction with the spatial surrounding by relying more on the visual information about the body at the beginning of an action and progressively more on the core representation of the body metrics once the imagined motor programming advances.

Critically, we were not interested in explicit distance judgment, but the indirect influence of distorted body representation on subjects' perception of their locomotion and interaction with the space around them. However, we did not exclude that the results reflect an effect of distance instead of walking time: if objects appeared nearer to the participants, they would show greater misestimation in their time-to-walk. In the final experiment, we directly assessed distance judgment, asking participant to verbally estimate the allocentric distance between two stimuli presented in a public space through 360° pictures. We used the same FBI paradigm to modify the perception of body metric, with the purpose to investigate the relationship between body size and distance computation in extra-personal.

Taking into account the baseline abilities of each participant in distance estimation, we found that the higher the overestimation at the beginning of the procedure, the higher the overestimation after the videos with the standard legs and the underestimation after the videos with the long legs. On the one hand, the body illusion can affect the most those subjects showing lower performances in judging distances. On the other hand, this result confirmed that being exposed to a video with a standard pair of legs enhances the overestimation of allocentric distances (Fini, Brass & Committeri 2014) and that seeing longer legs during a body illusion reduced such a perceived gap between points in far space, as in the previous experiment. This compression of lengths after a body illusion with longer legs seems to be consistent for both egocentric (van der Hoort et al., 2011) and allocentric distances.

Interestingly, we also asked participants to guess the number of steps they would have needed to walk the allocentric distance, and we found quite the opposite results. After the videos with the standard legs, independently from their orientation, the higher the overestimation at the baseline, the higher their underestimation after the body illusion, opposite to what we found for the distances in meters. The opposite pattern emerged in the case of the long legs: the higher the overestimation of judged steps at the baseline, the higher is the overestimation after the body illusion. This effect is more evident during the experimental condition than in the control one. When the long legs were embodied (anatomical condition) their size influenced the estimation of the number of steps as compared to the control condition to the most. We suggest that the lack of experience with such long legs could enhance the number of steps that participants imagined they would have needed to walk between landmarks, as if they adopted shorter steps for the sake of safety.

The present study confirmed that body illusions influence both the estimations of distances in meters and the number of steps. Indeed, the embodiment of longer legs, on the one hand, reduced the perceived overestimation in meters, on the other hand, produced an enhancement of the number of steps participants imagined they would have needed to walk between the same landmarks. Under the influence of the illusion of holding longer legs, i.e. the more or less conscious acquisition of a novel metric reference on the body, a more analytic and thus cautious estimation of length would be adopted by the observer. This would result in a reduced bias in the allocentric estimation of distance. Furthermore, this condition would determine an increased number of imagined steps to cover that distance due to the adoption of a shorter, more precise, stride.

In conclusion, we confirmed that the perception of body metric is distorted, both in healthy participants and in patients suffering from body representation disorders. Nevertheless, thanks to its plasticity, it is possible to induce provisional modifications of the body metric, employing body illusions. We showed that the process of embodiment could shape our perception of body metric. Moreover, such an induced manipulation seems to directly influence the perception of body affordances, our imagined interaction with the space around us and the estimation of allocentric distances in extrapersonal space.

From a scientific and theoretical point of view, the present work highlights the plastic characteristics of our body representation. Furthermore, it contributes to a better understanding of the relationship between our body and the space around us, suggesting an influence of body metric on the way we perceive our interaction with the environment and the perception of extrapersonal space. From a clinical point of view, these findings could be particularly meaningful in the development of intervention for those individuals suffering from motor deficit and impairment of body perception (Dohle et al., 2009; Flor et al., 2006; Hallett, 2001; Tosi et al., 2018).

The main limitation of the projects is the lack of replicability of experiment 6 that could be due to a different population since it was the only one conducted on a Canadian sample of participants. Indeed, experiment 6 was conducted during a visiting period in Canada, sampling from a different culture and using slightly different technology. In particular, the daily use of videogames and immersive devices in Canadian university students may have interfered with Body Illusion, creating a sort of habituation effect. Moreover, future studies will have to clarify the relationship between body metric perception and extrapersonal space, both in terms of distance perception and movement capabilities.

To the best of our knowledge, this is the first project studying step by step the relationship between modified body metric and allocentric distance perception in extra-personal space. The use of new technology in the present work, such as virtual reality, also represents a novel aspect in this kind of study. This technique, allowing to give a realistic, but at the same time strictly controlled, reconstruction of the bodily and extrapersonal space parameters to be studied, would allow the fruitful development of future research trying to link body and space representation in humans with both heuristic and clinical purposes.

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APPENDIX

Table 1. Illusory components of the subjective experience induced by the experimental procedure, and questionnaire items designed for their measurement.

FACTOR		ID	QUESTION
EMBODIMENT	**Ownership**	Q1	Did it seem like you were looking directly at your own legs?
		Q2	Did it seem like the legs in the video belonged to you?
	Agency	Q3	Did it seem like you could have moved the legs in the video if you had wanted?
		Q4	Did it seem like you were not in control of the legs in the video?
	Location	Q5	Did it seem like the legs in the video were in the location where your legs were?
		Q6	Did it seem like the touch you felt was caused by the stick touching the legs in the video?
LOSS OF OWN LEGS		Q7	Did it seem like your legs had disappeared?
		Q8	Did it seem like you could have moved your legs if you had wanted?
		Q9	Did it seem like your legs were out of your control?
		Q10	Did it seem like you couldn't really tell where your legs were?
DEAFFERENCE		Q11	Did it seem like the experience of your legs was less vivid than normal?
CONTROL		Q12	Did it seem like your own legs became "fake"?
		Q13	Did it seem like you had four legs?
SIZE		Q14	Did it seem like the stick was smaller, bigger or the same as the real one?
		Q15	Did it seem like the legs in the video were smaller, bigger or the same as your own?
AFFECT		Q16	Did you find that experience enjoyable?

Table 2. Results of the 2 (Session) *3 (Size) *2 (Orientation) repeated measures analysis of variance for each factor of the embodiment questionnaire in Experiment 1.

	df	**residual df**	**f**	**p**	**df**	**residual df**	**f**	**p**	**df**	**residual df**	**f**	**p**
	Ownership				*Agency*				*Location*			
Session	1	19	0.930	0.347	1	18	0.032	0.860	1	19	0.429	0.520
Size	2	38	38.568	< .001**	2	36	12.618	< .001**	2	38	12.754	< .001**
Orientation	1	19	9.065	< .05*	1	18	7.690	< .05*	1	19	49.717	< .001**
Session * Size	2	38	0.178	0.838	2	36	0.833	0.443	2	38	2.711	0.079
Session * Orientation	1	19	0.001	0.974	1	18	0.411	0.530	1	19	0.020	0.889
Size * Orientation	2	38	2.579	0.089	2	36	2.688	0.082	2	38	3.064	0.058
Session * Size * Orientation	2	38	0.237	0.790	2	36	3771	< .05*	2	38	1.139	0.331

	Loss of own legs				*Deafference*				*Control*			
Session	1	19	51.646	< .001**	1	1	4.013	0.060	1	19	3.711	0.069
Size	2	38	4.709	< .05*	2	2	0.542	0.586	2	38	0.049	0.953
Orientation	1	19	16.207	< .001**	1	1	2.073	0.166	1	19	0.093	0.764
Session * Size	2	38	19.178	< .001**	2	2	0.156	0.856	2	38	1.048	0.360
Session * Orientation	1	19	22.730	< .001**	1	1	1.160	0.295	1	19	6.897	< .05*
Size * Orientation	2	38	21.940	< .001**	2	2	1.092	0.346	2	38	0.019	0.981
Session * Size * Orientation	2	38	71.249	< .001**	2	2	1.215	0.308	2	38	0.882	0.447
	Size of the stick				*Size of the fake legs*				*Affect*			
Session	1	19	7.821	< .05*	1	19	0.098	0.758	1	19	0.666	0.424
Size	2	38	0.031	0.969	2	38	349.793	< .001**	2	38	2.327	0.111
Orientation	1	19	2.012	0.172	1	19	0.608	0.445	1	19	1.577	0.224
Session * Size	2	38	3.953	< .05*	2	38	1.036	0.365	2	38	0.979	0.385
Session * Orientation	1	19	0.263	0.614	1	19	1.923	0.182	1	19	1.029	0.323
Size * Orientation	2	38	0.468	0.630	2	38	3.405	< .05*	2	38	0.124	0.883
Session * Size * Orientation	2	38	1.264	0.294	2	38	0.054	0.947	2	38	2.365	0.108

Table 3. Bayesian Repeated Measure ANOVA model selection. We considered Response (Analogic/Discrete/Verbal) and Line Length (15/30) as within-subject factors, and the line presented in the first session (15/30) as between-subjects factor. The posterior distribution (P(M|data)) showed that the best fitting model is the null one. The Bayes Factors (BF_{01}) represent the probability of the best model on each one of the models it is compared to.

Models	**p(m)**	**p(m|data)**	**bf$_{m}$**	**bf$_{01}$**	**error %**
Null Model (Incl. Subject)	0.053	0.505	18.381	1.000	
First_Line	0.053	0.152	3.219	3.330	0.646
Line Length	0.053	0.142	2.987	3.550	2.700
Line Length + First_Line + Line Length * First_Line	0.053	0.064	1.237	7.858	2.811
Response	0.053	0.047	0.886	10.769	0.780
Line Length + First_Line	0.053	0.044	0.824	11.540	1.508
Response + Line Length	0.053	0.015	0.272	33.940	6.206
Response + First_Line	0.053	0.014	0.265	34.871	1.162
Response + Line Length + First_Line + Line Length * First_Line	0.053	0.006	0.113	81.105	3.108
Response + Line Length + First_Line	0.053	0.004	0.070	130.286	1.551
Response + First_Line + Response * First_Line	0.053	0.002	0.033	278.915	1.972
Response + Line Length + Response * Line Length	0.053	0.002	0.030	303.427	1.975
Response + Line Length + First_Line + Response * First_Line + Line Length * First_Line	0.053	8.017e -4	0.014	630.206	3.466
Response + Line Length + Response * Line Length + First_Line + Line Length * First_Line	0.053	7.765e -4	0.014	650.614	2.144
Response + Line Length + Response * Line Length + First_Line	0.053	5.141e -4	0.009	982.840	4.760
Response + Line Length + First_Line + Response * First_Line	0.053	4.951e -4	0.009	1020.563	2.035
Response + Line Length + Response * Line Length + First_Line + Response * First_Line + Line Length * First_Line	0.053	1.001e -4	0.002	5048.641	3.675
Response + Line Length + Response * Line Length + First_Line + Response * First_Line	0.053	6.582e -5	0.001	7676.546	3.042

Response + Line Length + Response * Line Length + First_Line + Response * First_Line + Line Length ✻ First_Line + Response * Line Length * First_Line	0.053	3.257e -5	5.863e -4	15512.536	2.982

Table 4. Linear Mixed Model (LMM) selection with the misestimation as the dependent variable. Fixed effects included were Session (I/II), Response (Analogic/Discrete/Verbal) and Line length (15/30). We set participants as a random effect variable. We run an Analyses of Variance (ANOVA) on the best model.

		Loglik	**Chisq**	**Chi df**	**Pr(>chisq)**
Selected Model	Misestimation ~ Session * Line length * Response + (1 | sog)	-47636			
Null Model	Misestimation ~ 1 + (1 | sog)	-48408	1543.9	11	≤.001
Fit1	Misestimation ~ Session + (1 | sog)	-48303	1333.6	10	≤.001
Fit2	Misestimation ~ Line length + (1 | sog)	-48177	1079.9	10	≤.001
Fit3	Misestimation ~ Response + (1 | sog)	-48177	1081.1	9	≤.001
Fit4	Misestimation ~ Session * Line length + (1 | sog)	-48066	860.1	9	≤.001
Fit5	Misestimation ~ Session + Response + (1 | sog)	-48067	861.04	8	≤.001
Fit6	Misestimation ~ Session * Line length + (1 | sog)	-48066	859.85	8	≤.001
Fit7	Misestimation ~ Line length + Response + (1 | sog)	-47934	595.89	8	≤.001
Fit8	Misestimation ~ Session * Line length + (1 | sog)	-48066	859.85	8	≤.001
Fit9	Misestimation ~ Session + Line length + Response + (1 | sog)	-47819	365.28	7	≤.001
Fit10	Misestimation ~ Line length * Response + (1 | sog)	-47848	424.2	6	≤.001
Fit11	Misestimation ~ Session * Line length + Response + (1 | sog)	-47819	365.12	6	≤.001
Fit12	Misestimation ~ Session + Line length * Response + (1 | sog)	-47731	189.9	5	≤.001

Table 5. Series of model comparisons between LMM ANOVAs on the misestimation in each condition independently. Fixed effects included were the Direction (medio-lateral axis/proximo-distal axis), the Distance (near/far), and the Order of the stimuli presentation (AB order/BA order). We set participants as a random effect variable. We run an Analyses of Variance (ANOVA) on the best model.

Analogic 15cm Line		**Loglik**	**Chisq**	**Chi df**	**Pr(>chisq)**
Selected Model	Misestimation ~ Direction * Order + Distance + (1 | sog)	-3977.0			
Null Model	Misestimation ~ (1 | sog)	-3993.3	32.77	4	≤.001
Fit1	Misestimation ~ Direction + Order * Distance + (1 | sog)	-3980.5	0	0	1
Fit2	Misestimation ~ Direction * Order * Distance + (1 | sog)	-3975.6	2.6323	1	0.45

Best Model	numdf	dendf	f	p
Direction	1	834	14.53	≤.001
Order	1	834	0.51	0.48
Distance	1	834	9.73	≤.05
Direction:Order	1	834	8.46	≤.05

Analogic 30cm Line		Loglik	Chisq	Chi Df	Pr(>Chisq)
Selected Model	Misestimation ~ Direction + (1 | sog)	-3867.4			
Null Model	Misestimation ~ (1 | sog)	-3882.5	12.324	1	≤.001
Fit2	Misestimation ~ Order + (1 | sog)	-3881.4	0.00	0	1
Fit3	Misestimation ~ Distance + (1 | sog)	-3882.5	0.00	0	1
Fit4	Misestimation ~ Direction + Order + (1 | sog)	-3875.2	2.25	1	0.13
Fit5	Misestimation ~ Direction + Distance + (1 | sog)	-3876.4	4e-04	1	0.98
Fit6	Misestimation ~ Direction + Order + Distance + (1 | sog)	-3875.2	2.25	2	0.33
Fit7	Misestimation ~ Direction * Order + (1 | sog)	-3874.5	3.68	2	0.16
Fit8	Misestimation ~ Direction * Distance + (1 | sog)	-3876.2	0.22	2	0.90
Fit9	Misestimation ~ Direction * Order * Distance + (1 | sog)	-3873.8	5.19	6	0.52

Best Model	numdf	dendf	f	p
Direction	1	839	12.4	≤.001

Discrete 15cm Line		Loglik	Chisq	Chi Df	Pr(>Chisq)
Selected Model	Misestimation ~ Direction + Distance + (1 | sog)	-4065.5			
Null_Model	Misestimation ~ 1 + (1 | sog)	-4075.7	20.18	2	≤.001
Fit1	Misestimation ~ Direction + Distance + Order + (1 | sog)	-4065.5	0.20	1	0.66
Fit2	Misestimation ~ Direction * Order + (1 | sog)	-4068.6	0	1	1
Fit3	Misestimation ~ Direction * Distance + (1 | sog)	-4065.5	0.14	1	0.71
Fit3	Misestimation ~ Order * Distance + (1 | sog)	-4070.1	0	1	1
Fit4	Misestimation ~ Direction + Distance * Order + (1 | sog)	-4065.3	0.67	2	0.71
Fit5	Misestimation ~ Direction * Order * Distance + (1 | sog)	-4062.9	5.30	5	0.38

Best Model	numdf	dendf	f	p

Direction	1	838	9.72	≤.05
Distance	1	838	10.65	≤.001

Discrete 30cm Line		**Loglik**	**Chisq**	**Chi Df**	**Pr(>Chisq)**
Selected Model	Misestimation ~ Direction + (1 | sog)	-3875.5			
Null_Model	Misestimation ~ 1 + (1 | sog)	-3883.4	15.759	1	≤.001
Fit1	Misestimation ~ Order + (1 | sog)	-3882.8	0	0	1
Fit2	Misestimation ~ Distance + (1 | sog)	-3883.2	0	0	1
Fit3	Misestimation ~ Direction + Order + (1 | sog)	-3875.2	0.52	1	0.47
Fit4	Misestimation ~ Direction + Distance + (1 | sog)	-3876.4	0	1	1
Fit5	Misestimation ~ Direction * Order + (1 | sog)	-3874.5	1.96	2	0.37
Fit6	Misestimation ~ Direction * Distance + (1 | sog)	-3876.2	0	2	1
Fit7	Misestimation ~ Direction + Order + Distance + (1 | sog)	-3875.2	0.52	2	0.77
Fit8	Misestimation ~ Direction * Order * Distance + (1 | sog)	-3873.5	3.47	6	0.75

Best Model	**numdf**	**dendf**	**f**	**p**
Direction	1	839	15.89	≤.001

Verbal 15cm Line		**Loglik**	**Chisq**	**Chi Df**	**Pr(>Chisq)**
Slected Model	Misestimation ~ Direction * Order + (1 | sog)	-4112.9			
Null_Model	Misestimation ~ 1 + (1 | sog)	-4120.0	14.13	3	≤.05
Fit1	Misestimation ~ Direction * Distance + (1 | sog)	-4115.6	0	0	1
Fit2	Misestimation ~ DIrection * Order + Distance + (1 | sog)	-4112.9	0.13	1	0.72
Fit3	Misestimation ~ Direction * Order * Distance + (1 | sog)	-4112.3	1.27	4	0.87

Best Model	**numdf**	**dendf**	**f**	**p**
Direction	1	837	7.77	≤.05
Order	1	837	0.08	0.78
Direction:Order	1	837	6.34	≤.05

Verbal 30cm Line		**Loglik**	**Chisq**	**Chi Df**	**Pr(>Chisq)**
Selected Model	Misestimation ~ Direction + Distance + (1 | sog)	-4085.5			

<table>
<tr><td>Null_Model</td><td>Misestimation ~ 1 + (1 | sog)</td><td>-4102.6</td><td>34.26</td><td>2</td><td>≤.001</td></tr>
<tr><td>Fit1</td><td>Misestimation ~ Direction + Distance + Order + (1 | sog)</td><td>-4085.4</td><td>0.17</td><td>1</td><td>0.68</td></tr>
<tr><td>Fit2</td><td>Misestimation ~ Direction * Distance + (1 | sog)</td><td>-4085.1</td><td>0.86</td><td>1</td><td>0.35</td></tr>
<tr><td>Fit3</td><td>Misestimation ~ Direction + Distance * Order + (1 | sog)</td><td>-4085.3</td><td>0.31</td><td>2</td><td>0.85</td></tr>
<tr><td>Fit4</td><td>Misestimation ~ Direction * Order * Distance + (1 | sog)</td><td>-4083.6</td><td>3.74</td><td>5</td><td>0.59</td></tr>
</table>

Best Model	**numdf**	**dendf**	**f**	**p**
Direction	1	838	22.80	≤.001
Distance	1	838	12.09	≤.001

Table 6. Results of the 3 (Size) *2 (Orientation) repeated measures analysis of variance for each factor of the embodiment questionnaire in Experiment 3.

	df	**residual df**	**f**	**p**	**df**	**residual df**	**f**	**p**	**df**	**residual df**	**f**	**p**
	Ownership				*Agency*				*Location*			
Size	2	46	38.663	< .001**	2	46	3.656	< .05*	2	46	12.592	< .001**
Orientation	1	23	0.821	0.374	1	23	0.014	0.906	1	23	26.690	< .001**
Size * Orientation	2	46	0.095	0.909	2	46	0.123	0.885	2	46	0.821	0.446
	Loss of own legs				*Deafference*				*Control*			
Size	2	46	1.538	0.226	2	46	1.540	0.225	2	46	2.040	0.142
Orientation	1	23	0.213	0.649	1	23	3.881	0.061	1	23	0.211	0.650
Size * Orientation	2	46	0.778	0.465	2	46	1.428	0.250	2	46	0.193	0.825
	Size of the stick				*Size of the fake legs*				*Affect*			
Size	2	46	0.519	0.599	2	46	156.655	< .001**	2	46	10.252	< .001**
Orientation	1	23	1.166	0.291	1	23	5.239	< .05*	1	23	3.712	0.066
Size * Orientation	2	46	1.620	0.209	2	46	0.147	0.864	2	46	0.011	0.989

Table 7. Results of the 2 (Size) *2 (Orientation) repeated measures analysis of variance for each factor of the embodiment questionnaire in Experiment 6.

	df	**residual df**	**f**	**p**	**df**	**residual df**	**f**	**p**	**df**	**residual df**	**f**	**p**
	Ownership				*Agency*				*Location*			
Size	1	40	18.393	< .001**	1	40	5.998	< .05*	1	40	15.859	< .001**
Orientation	1	40	21.761	< .001**	1	40	0.939	0.338	1	40	45.740	< .001**
Size * Orientation	1	40	0.033	0.858	1	40	0.003	0.858	1	40	4.046	0.051
	Loss of own legs				*Deafference*				*Control*			
Size	1	39	1.849	0.182	1	40	0.032	0.860	1	40	0.416	0.523
Orientation	1	39	0.122	0.729	1	40	1.234	0.273	1	40	1.083	0.304

Size * Orientation	1	39	1.849	0.182	1	40	0.870	0.357	1	40	3.907	0.055
	Size of the stick				*Size of the fake legs*				*Affect*			
Size	1	40	1.313	0.259	1	40	108.053	< .001**	1	40	0.039	0.844
Orientation	1	40	1.042	0.313	1	40	7.295e-4	0.979	1	40	1.288	0.263
Size * Orientation	1	40	0.017	0.897	1	40	3.424	0.072	1	40	0.606	0.441

Table 8. Results of the 2 (Size) *2 (Orientation) repeated measures analysis of variance for each factor of the embodiment questionnaire in Experiment 7.

	df	**residual df**	**f**	**p**	**df**	**residual df**	**f**	**p**	**df**	**residual df**	**f**	**p**
	Ownership				*Agency*				*Location*			
Size	1	23	0.027	0.782	1	23	0.199	0.660	1	23	1.772	0.196
Orientation	1	23	10.925	< .05*	1	23	1.880	0.184	1	23	40.413	< .001**
Size * Orientation	1	23	0.636	0.433	1	23	0.381	0.543	1	23	0.235	0.633
	Loss of own legs				*Deafference*				*Control*			
Size	1	23	5.537	< .05*	1	23	1.487	0.235	1	23	5.543	< .05*
Orientation	1	23	2.436	0.132	1	23	1.044	0.317	1	23	2.851	0.105
Size * Orientation	1	23	0.717	0.406	1	23	2.858	0.104	1	23	0.070	0.794
	Size of the stick				*Size of the fake legs*				*Affect*			
Size	1	23	0.648	0.429	1	23	101.478	< .001**	1	23	0.425	0.521
Orientation	1	23	0.376	0.546	1	23	0.071	0.792	1	23	4.548	0.044
Size * Orientation	1	23	1.846	0.187	1	23	1.711	0.204	1	23	5.916	0.023

Table 9. Results of the Linear Mixed Model (LMM) analysis between Condition (Mirror/no-Mirror) and Strength (Mild impairment/Strong impairment).

	numdf	**dendf**	**f**	**p**
Condition	1	1305.8	48.40	< .001**
Strength	1	43.0	0.02	0.891
Condition * Strength	1	1305.8	8.49	0.004

Table 10. Results of the Linear Mixed Model (LMM) analysis between Condition (Mirror/no-Mirror) and Tactile perception (Mild impairment/Strong impairment).

	numdf	**dendf**	**f**	**p**
Condition	1	1304.9	6.96	<.05*
Tactile Perception	1	43.0	3.82	0.057
Condition * Tactile Perception	1	1304.9	17.48	< .001**

Table 11. Results of the Linear Mixed Model (LMM) analysis between Condition (Mirror/no-Mirror) and Proprioception (Compromised/Speared).

	numdf	dendf	f	p
Condition	1	1249.0	264.030	< .001**
Proprioception	1	41.0	0.0699	0.793
Condition * Proprioception	1	1249.0	49.256	<.05*

Table 12. Results of the Linear Mixed Model (LMM) analysis between Condition (Mirror/no-Mirror) and Personal neglect (Absent/Present).

	num df	den df	f	p
Condition	1	1245.6	5.470	<.05*
Personal Neglect	1	41.0	3.384	0.073
Condition * Personal Neglect	1	1245.6	0.214	0.644