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THE EFFECT OF MIRROR BOX ILLUSION ON THE LINE BISECTION TASK

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ABSTRACT

The body is ever-present to experience. Even when it is not the direct object of perception, it is embedded in first-person perspective. It is the material recipient for the sense of self, as well as the effector providing the sense of agency. Body representations show an impressive degree of plasticity, especially during finalized actions, where even external objects can be incorporated to carry out tasks. Such modifications have repercussions on various cognitive domains. This study aims to investigate how the embodiment of an external object can modulate spatial representation. An extensive corpus of works has examined the influence of body representations changes on peripersonal space. However, the understanding of the influence of the body on the representation of space is still limited. To deepen the understanding of this relation, 36 healthy participants were employed in a Mirror Box Illusion (MBI) paradigm. Participants were asked to tap at both ends of the Mirror Box to create the illusion of ownership towards the hand reflected in the mirror. Before and after this stimulation, participants were asked to complete an Embodiment Questionnaire and to carry out a Localization Task and a Line Bisection Task. Participants' subjective reports portrayed the effect of the illusion, with items describing subcomponents of embodiment displaying higher scores after the synchronous stimulation. The localization task reported a systematic mislocalization of the biological limb and a shift of its perceived location towards the mirrored hand. This proprioceptive drift was present not only after synchronous stimulation but also after the asynchronous tapping when the right hand was visible. Subjective sense of embodiment and proprioceptive drift displayed a significant correlation, where the more participants reported the illusion as vivid, the more proprioceptive drift they displayed. Together, these results advocate for the efficacy of the MBI in inducing the embodiment of the reflected hand. Conversely, the line bisection task did not show any effect of the MBI stimulation. Despite the shift in the subjective body midline attested in the localization task, participants did not show any significant change in how they bisected the lines after the stimulation. Therefore, the modifications in body representations caused by the Mirror Box Illusion did not elicit any reported effect on the representation of space.

Keywords: Mirror Box Illusion, Embodiment, Ownership, Proprioceptive Drift, Line Bisection, Body Representation, Space Representation

1: INTRODUCTION

In “Meditations on First Philosophy” (Descartes, 2013) the 17th century French intellectual René Descartes is questioning reality. Being taken by what he describes as a hyperbolic doubt, the philosopher falls victim to a paranoid belief: an evil demon is manipulating him, creating an illusion, a simulation, where everything feels real but is not. Descartes's resolution to his belief is to question every single aspect of reality. However, whilst doing so, the brilliant philosopher realizes that there is only one thing he can be certain of: “Cogito, ergo sum”. He could doubt reality, he could suspect his perception, his sensations, his feelings, and even the fact that he possesses a body, but this same suspicion was the living proof of his mind.

In Descartes's view this *thinking thing*, which he called “res cogitans”, is an immaterial substance, the essence of himself who doubts, believes, hopes, and thinks, his mind and soul. On the other hand, “res extensa” is the thing that exists, the body that pertains to the physical world, which is susceptible to error and query. Res cogitans and res extensa, mind and body, are distinct and separate entities, thus shaping a hard dualism where interaction between the two is problematic.

Numerous have been the arguments against Cartesian dualism; the arguments opposing it range from philosophy to biology to even neuropsychology. As a case in point, Phineas Gage’s story (Damasio et al., 1994) highlights the interaction between mind and body.

On September 1848, Phineas Gage, a 25-year-old construction foreman for a railroad, was the victim of a particular accident. Due to distraction, an explosion occurred in the workplace, leading the iron rod that Gage was maneuvering to blast vertically in the air, piercing the workman’s face, skull, and brain. Despite being hit by the powerful blast, Gage managed to gain back consciousness immediately thereafter. The peculiarity of the case doesn’t stop with

Gage outliving the injury; he survived as a different man than before the accident. Everyone who knew him described him as a responsible, intelligent, and socially well-adapted individual. During the convalescence, his physician, John Harlow, noticed significant changes in Gage's personality (Harlow, 1993). In Harlow's report is evident that Gage remained as able-bodied and appeared as intelligent as before the accident; he had no impairment of movement or speech. New learning was intact, and neither memory nor intelligence in the conventional sense had been affected. However, he had become irreverent and capricious. His respect for the social conventions came less and his profanities offended those around him. Indubitably, the most significant change in Gage's personality was his sense of responsibility. His employers considered him 'the most efficient and capable' man in the team, but now had to dismiss him. In the words of his friends and acquaintances, 'Gage was no longer Gage' (Harlow, 1993). Twenty years after the accident, John Harlow perceptively correlated Gage's cognitive and behavioural changes with a presumed area of focal damage in the frontal region of the brain. As modern analysis (Ratiu et al., 2004) shows, the physician's intuition was correct; structures in Gage's brain dedicated to the planning and execution of socially suitable behaviour and the aspect of reasoning behind rationality had been critically damaged, leading to the change in personality. A change in the body had led to a change in the mind.

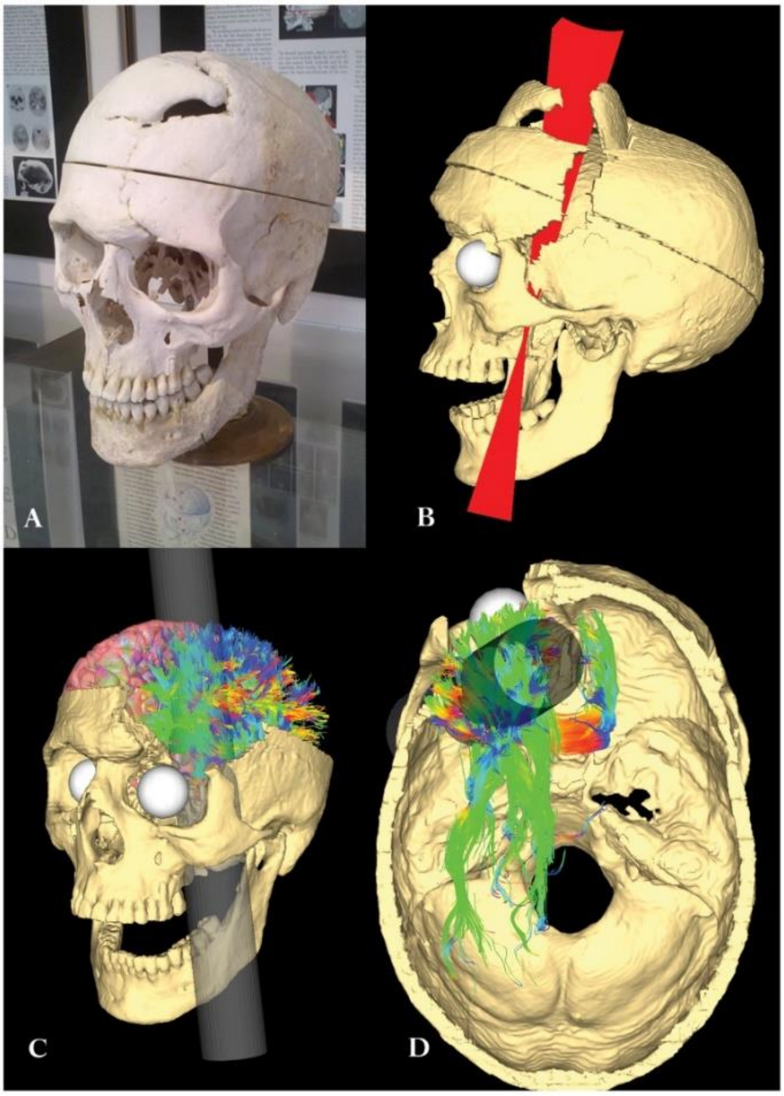

Figure 1: Modelling the path of the tamping iron through the Gage skull and its effects on white matter structure (Horn et al., 2012).

A) The skull of Phineas Gage on display at the Warren Anatomical Museum at Harvard Medical School. B) Reconstruction of the trajectory of the rod. CT image volumes were reconstructed, spatially aligned, and manual segmentation of the individual pieces of bone dislodged by the tamping iron (rod), top of the cranium, and mandible was performed. Surface meshes for each individual element of the skull were created. C) A rendering of the Gage skull with the best fit rod trajectory and example fiber pathways in the left hemisphere intersected by the rod. D) A view of the interior of the Gage skull showing the extent of fiber pathways intersected by the tamping iron in a sample subject.

Lesional case studies are not the only argument against a mind-body separation. Indeed, cartesian dualism is firmly criticized by French phenomenologist Maurice Merleau-Ponty. In his work: "Phenomenology of Perception" (Merleau-Ponty, 2011), the philosopher emphasizes the embodied nature of perception, which is not only a function of the mind, but is intimately tied to the body. Separation between mind and body is impossible, since bodily experiences and movements are key factors in shaping the perception of the world. This impact of the body on perception takes place at an implicit level, thanks to body schemas, which are pre-reflective, tacit knowledge of our bodies and their capabilities. These representations organize perception and interaction with the world, allowing space navigation.

The present work aims at defining the complex interaction between body representations and spatial representations. Initially, it will focus on describing the main features of body representations, as well as illustrating the plasticity of such representations. Bodily self-awareness will be discussed, along with the feeling of body-ownership and embodiment, that allows one to locate one's body outside of oneself anatomical borders. Spatial representations will take the spotlight as the introductory part continues. Specifically, the central section will revolve around the peripersonal space, the portion of space surrounding the body. At last, an attempt to define the conundrum behind the modulatory aspects of body representations on spatial representations. Along this discussion, neuropsychological, as well as neurophysiological and neuroimaging evidence will be presented to support this thesis: how the body is represented changes the representation of the space surrounding it.

1.1: Body Representations

The body is ubiquitous to experience. It works as a vessel to our sense of self, whose extension corresponds to the surface of our skin. Sense of identity, self-esteem, and overall mental health are deeply influenced by the way one's body is perceived. It is also the prevalent way to interact with the external world, allowing action as well as a sense of agency (Azañón et al., 2016; Longo, 2015a).

Moreover, the body channels both internal and external sensations and it allows first-person perspective. This way, each person has an immediate awareness of their body from the inside, as an object of direct perception. On the other hand, one's body is also a physical object, like any other in the world, subject to gravity and affected by external forces. Consequently, It is possible to ponder on the body from a detached point of view, as one would normally do with a physical or biological object (Longo, 2015b). Hence the possibility to distinguish the variety of body representation under two categories: somatoperception and somatorepresentation (Longo et al., 2010).

Somatoperception refers to the process of constructing perceptions and experiences of somatic objects and events. Altogether, it defines one's own body and its interaction with external cues. Unique among sensory modalities, the somatic receptor surface (the skin) is coextensive with the body surface. Specifically, for veridical somatosensory percepts to be processed, they must be referenced to, and informed by, pre-existing representations of the body. This comparison allows the reorganization of information from the body surface into an egocentric reference frame. In addition, it plays a major role in integrating interoceptive perception about the state of the body and exteroceptive perception of objects in the external world through their contact with the body. Thus, somatoperception involves some cases in which the body is a vehicle for perception, and others in which it is itself the object of perception (Longo et al., 2010).

Somatorepresentation, in contrast, refers to the essentially cognitive process of constructing semantic knowledge and attitudes about the body. It includes lexical semantic knowledge about bodies in general, and one's own body specifically, but also conceptual knowledge about body structure, emotions, and attitudes towards one's body and the link between physical body and psychological self. Particular instances illustrate the distinction and even the conflict between body representations. It is the case of individuals with phantom limbs syndrome following amputations, where the missing limb is perceived as present, even though the amputee is well aware of its absence (Melzack, 1992; Ramachandran & Hirstein, 1998).

Considering that, to this day, there isn't any comprehensive theory regarding the link between the two, it is still useful to take a speculative model (Longo, 2015b) as a reference. This thesis will follow Longo's classification in an attempt to define the multi-faceted and often variable concept of body representation. In their work, Longo and colleagues organize body representation via two axes, ranging from explicit to implicit and from perceptual to conceptual. This rationale allows to distinguish body representations revolving around somatoperception, which are body image, body model, superficial schema, and body schema, from the ones insisting on somatorepresentation, such as body semantics and body structural description. This work will focus on the former.

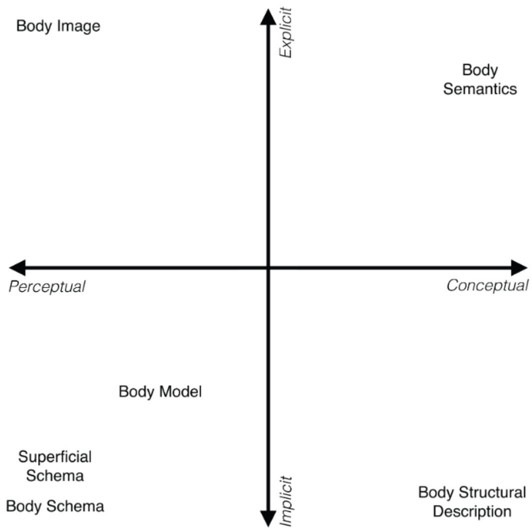

Figure 2: Types of Body Representation (Longo, 2015b).

1.1.1: Body Image

Body image refers to the subjective, conscious experience of the physical aspects of the body, such as size, shape, and physical composition. In healthy people, body image is generally accurate in representing the corporal structural aspects. Nevertheless, there are instances where the subjective experience of the body can be inaccurate, or even distorted. This is the case for body image disturbances in eating disorders and other conditions such as body dysmorphic disorder (Phillips & Hollander, 2008). A non-pathological instance of body image distortion is undergoing local anaesthesia (Gandevia & Phegan, 1999). After being subjected to thumb anaesthesia, blindfolded participants reported an increase in the size of that particular finger. This created a conflict between the immediate somatosensory experience and beliefs about the body. Indeed, participants were fully aware that their thumb hadn't changed in size, yet they couldn't help but feel such an increase.

There's an ever-growing number of studies showing that people's subjective experience of their body can be altered, even as people know it hasn't. Amongst them, the rubber hand illusion (RHI) has highlighted the extension of this alteration. The illusion revolves around a prosthetic hand, placed in front of the participant, and touched in synchrony with the participant's unseen hand (Botvinick & Cohen, 1998). After being subjected to such stimulation, participants reported feeling like the artificial hand was actually their own hand. Specifically, they felt the touch on the rubber hand, not on their hidden hand, as if their arm had embodied the fake limb. However, when the participant's hand and the rubber counterpart were asynchronously stroked, the illusion didn't take place. Successive variations on this paradigm showed additional features of this phenomenon, such as altering the perception of the relation between oneself and the rubber hand (Longo et al., 2009). Participants who had experienced the rubber hand illusion reported significantly greater similarity between the artificial limb and their own hand when compared to a control group. The incorporation of the rubber hand into the body image modulated similarity judgement between the hands. Further discussion on rubber hand illusion and embodiment will follow. However, this preliminary evidence is enough to exhibit the plasticity of the body image.

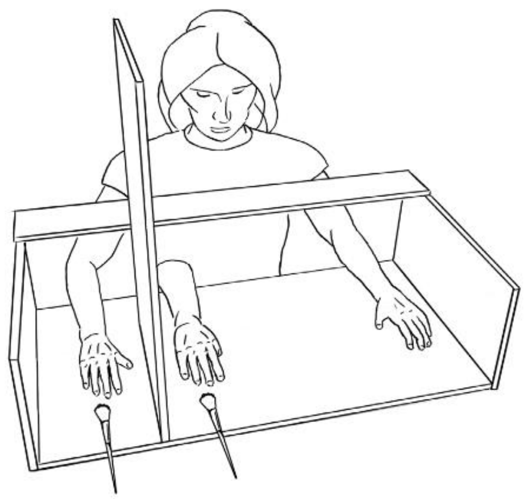

Figure 3: Rubber Hand Illusion (de Haan et al., 2017).

1.1.2: Body Schema

Aside from particular situations such as the ones discussed above, the body image is generally stable through time, due to the fact that the size and the shape of one's own body are fixed, or rather, they change very slowly. On the other hand, the posture and orientation of the body in space change constantly as one moves in the environment. The body schema keeps track of these continuous shifts and refers to a more dynamic representation of body posture (Head & Holmes, 1911). The main properties of this representation are to be finalized to action, to be dynamically updated, and strictly internally coherent. Whenever a person grabs a cup, the displacement of his/her fingers around the handle is automatic. Nevertheless, to accurately reach and grasp the object, the brain needs to integrate multiple information. Position, shape, and dimension of the target, but also of its own body, and, in particular, of the body part that will execute the action: these are all the factors taken into account to execute even the simplest task. Body parts' spatial positions and dimensions are computed by combining information coming from different somatosensory modalities, such as proprioception, kinaesthesia, and touch, into a sensory-motor schema. Going back to Longo's classification, the body schema is still a representation based on perception, but contrary to body image it operates without conscious awareness, to guide and control action and movement in the world. As a case in point, Castiello et al. (1991) asked participants to reach for visual objects which were suddenly displaced after reach onset. Stimuli were presented, but as soon as participants began the reaching motion, the targets were moved. To adjust to such change, they corrected their trajectory more than 300 ms before they were consciously aware of the displacement. Similar prowess is often displayed in sports. A fitting example would be dodgeball, where the pace of the game forces players to dodge erratically balls that are too fast to (consciously) follow with the eye. The body simply moves and dodges successfully, most of the time.

A key property of body schema is its plasticity, as stated in the seminal paper by Head & Holmes (1911): " By means of perpetual alterations in position we are always building up a postural model of ourselves which constantly changes. Every new posture or movement is recorded on this plastic schema, and the activity of the cortex brings every fresh group of sensations evoked by altered posture into relation with it. Immediate postural recognition follows as soon as the relation is complete".

Hence, two ideas follow:

1) The body schema is essentially a sensorimotor representation, as proprioceptive, kinaesthetic, and tactile information contribute to building it.
2) Its updating takes place at an unconscious level, without needing an attentive effort.

Once the update is completed it is possible to consciously report the position of the body.

1.1.3: Proprioception

Although body schema is a fundamental representation for movement and action, it's been documented an instance where walking and other tasks were possible despite an impairment in the schema (Gallagher & Cole, 1995). Patient I. W. suffered a near-complete loss of afferent signals at the spinal level, producing a total disturbance in proprioception without an associated deficit in the ability to send motor commands. Proprioception refers to the sense of position of the parts of the body. It provides feedback on the body's own actions, combining efferent information about limb position and movement, including effort, force, and balance (Feldman & Latash, 1982) together with afferent information from somatosensory receptors in the skin, viscera, muscles, spindles, tendon organs and joints (Marieb & Hoehn, 2007). Altogether, these information are centrally processed by multimodal neurons in the posterior parietal cortex (Kammers et al., 2006).

As stated above, it plays a key role in defining the body schema. Hence, an impairment in proprioception as displayed in I. W.'s clinical case, leads to disrupting the body schema (Gallagher & Cole, 1995). Initially, the patient was almost entirely unable to produce skilled actions. However, through intense practice, I. W. re-learned to walk and perform many other daily activities using continuous and intense visual guidance. In other terms, he had to constantly refer to his conscious body image, to achieve what would have otherwise been carried unconsciously by the body schema.

1.1.4: Superficial Body Schema

Body schema depicts proprioceptive and kinaesthetic information about the body before and after movement. Conversely, superficial body schema accounts for the localization of sensation on the body surface. In this representation, information from primary somatosensory representations is mapped to a representation of body form, that allows the allocation of tactile stimuli on the skin (Medina & Coslett, 2010). Longo, (2015) describes superficial body schema as an implicit representation. Evidence supporting this theory comes from the case study revolving around R.S. (Paillard, 1999). The centrally deafferented patient (R. S.) was unable to detect or perceive any static tactile stimulation on her right lower arm and failed to verbally report the spatial position of this stimulated area. Nevertheless, she was perfectly able to indicate with her intact arm on the deafferented hand where she had been touched. Being astonished by what had happened she commented:

"But, I don't understand that. You put something there; I do not feel anything and yet I got there with my finger. How does that happen?".

The statement, together with her behaviour, testify for R. S. capabilities: clear localization without sensory detection. She displayed an intact implicit body representation despite the lack of an explicit equivalent. A similar case has been discussed by Rossetti et al. (1995).

Defined as ‘blind touch’, this condition interests not only the body schema, but also the superficial schema. The distinction between the two schemas is clear in cases such as atopognosia. The latter is a condition where patients are unable to judge where on the skin they have been touched despite being aware of the touch and the limb posture. Conversely, Head & Holmes (1911) described patients who could localize touch on their body, but could not localize their limbs in space.

1.1.5: Body Model

Lastly, the body model accounts for the need to match and locate sensory signals to a stored representation of body size and shape. Several forms of perception require immediate sensory signals to be combined with information about the size and shape of the body. For example, to perceive the distance of the object from the observer, the convergence angles of the eyes are informative, but only if the distance between the eyes is known (Banks, 1988). Similarly, the difference in time of a sound reaching the two ears can be used to perceive the direction from which the sound is coming, but only if the distance between the ears is known (Clifton et al., 1988). Additionally, the body model acts as a reference frame for the construction of veridical somatosensory percepts by comparison to pre-existing representations of the body. Both body model and body image represent the size and shape of the body. Therefore, there is no obvious reason why the latter couldn’t be used as the former for all perceptual tasks. However, what separates the two of them is the susceptibility that the body model shows to large distortions, to which the body image stays untouched. An example of this dissociation can be found in the task of localizing the absolute position of the body in space. To achieve such a task, one has to combine the immediate afferent signals specifying joint angles, together with a stored representation of body size and shape. Longo & Haggard (2010) developed a procedure to isolate and measure this representation. Participants placed their hands on a table underneath an occluding board and used a stick to indicate where they perceived the knuckle and the tip of each finger. In the analysis of this task, experimenters focused on the internal configuration of judgments when compared to each other, ignoring the actual location of the hand. This allowed them to construct perceptual maps of how participants represented the structure of the hand, which could then be compared to the actual hand shape. These maps were highly distorted in a stereotyped fashion across participants. Three clear patterns of distortion emerged: (1) an overestimation of the width of the hand, (2) an underestimation of the length of fingers, and (3) a progressive increase in the underestimation of finger length from the thumb to the little finger. An effective depiction of the plasticity of the Body Model is displayed in Fig. 4.

However, when Longo and Haggard asked participants to select from an array of hand images the one most like their own, they were quite accurate. Such difference in participants' performance across tasks suggests that the body image maintains more veridical information about body shape than the body model. Critically, even though the brain has access to a veridical representation of the hand shape (provided by the body image), the highly distorted body model is still used to localize the body in space. Hence, the process of localization of body parts in space and the associated body model are, at least in part, cognitively impenetrable. This can be explained by considering how the body model works; it compares online, changing sensory information together with an offline, stable, and fixed representation of the body.

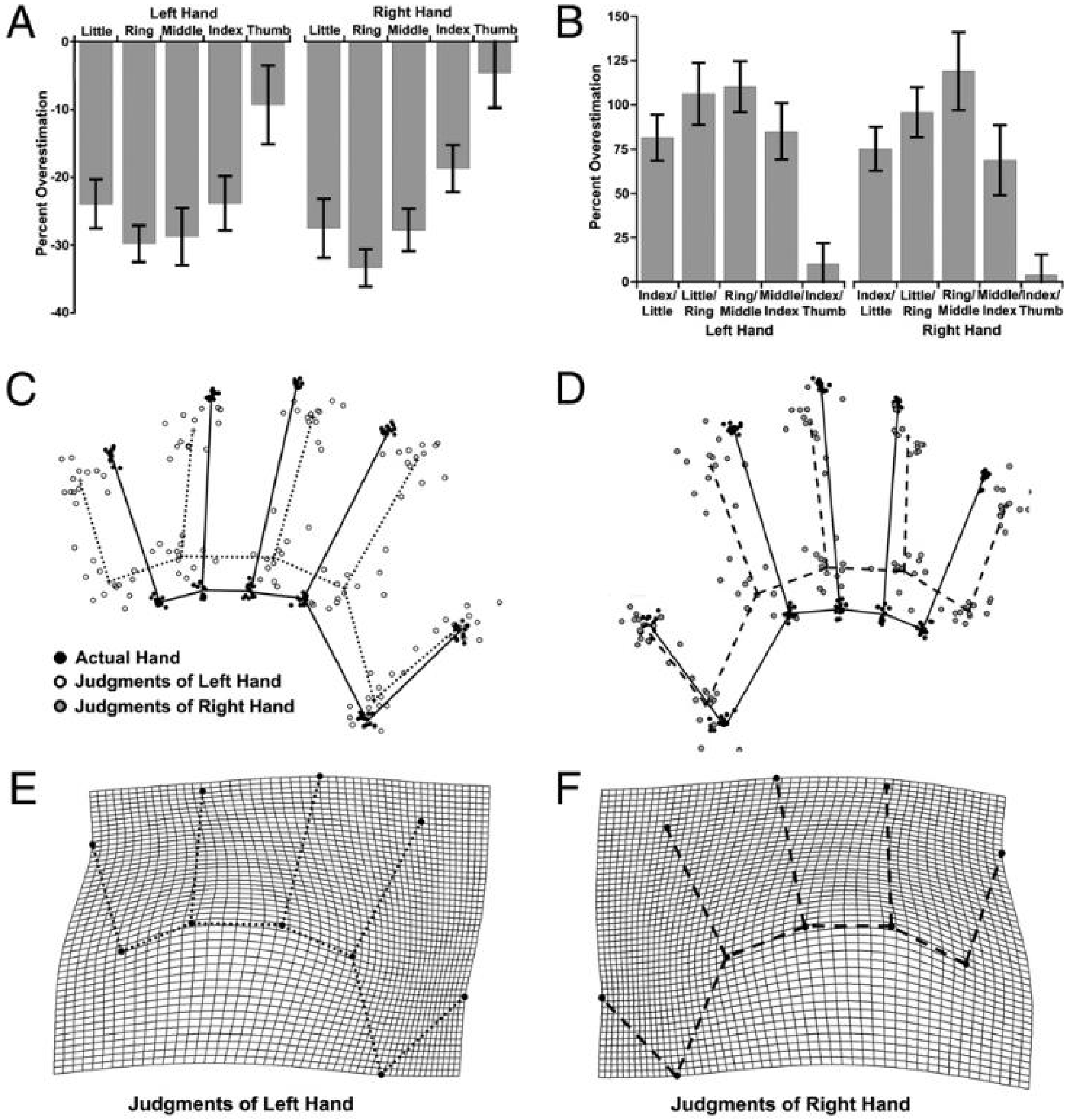

Figure 4: Body Model Distortion (Longo & Haggard, 2010)

(A) Percent overestimation of finger lengths for left and right hands. (B) Percent overestimation of knuckle spacings for the two hands. (C) GPS of actual left hands (black dots/black lines) and left hand body model (white dots/dotted lines). (D) GPS of actual right hands (black dots/black lines) and right hand body model (gray dots/dashed lines). (E) Thin-plate spline depicting shape of left hand body model as a deformation of actual hand shape. (F) Comparable thin-plate spline for right hand body model

1.1.6: Body Ownership

Altogether, body representations deliver an integrated multisensory depiction of the body. However, for one to be recognized within their body, for their sense of self to be bound to these kinds of renditions, body representations alone are not sufficient. The individual psychological identity between the self and its body is intimately related to the feeling of owning that body (Cassam, 1997). Trying to define all the components involved in tying the body to the self is an impervious task. For this work, the focus will be on the sense of ownership. In other words, "body ownership refers to the special perceptual status of one's own body, which makes bodily sensations seem unique to oneself, that is the feeling that "my body" belongs to me, and is ever present in my mental life" (Gallagher, 2000; Tsakiris, 2017). Ownership stems from multiple sensory inputs, particularly proprioceptive and visual inputs (Giummarra et al., 2008; Tsakiris, 2017). Consequently, multisensory integration paradigms have been used to address the necessary conditions for a body to be perceived as "mine". Among many, the rubber hand illusion has proven its efficacy in manipulating the experience of body ownership, hence giving insight into its functioning. As discussed above, synchronous multisensory stimulation (visuo-tactile in most cases) effectively creates the illusion of owning the rubber hand. By synchronously stroking the rubber hand together with the real hand, the experimenter elicited in participants the feeling of ownership over the artificial limb (Botvinick & Cohen, 1998). Since their real hand was hidden from view, seeing the rubber hand being stroked captured the tactile sensation on the biological limb, resulting in a mislocalization of the tactile stimulus. When the apparent visual location of a body part conflicts with its veridical location, vision can dominate proprioception and kinaesthesia. As a result, vision can capture tactile localization (Pavani et al., 2000). Consequently, participants experienced a shift of their own unseen hand towards the spatial location of the visual percept, resulting in the feeling of ownership of the artificial limb. This is the outcome of multisensory processing trying to resolve conflicting sensory information. Rubber hand illusion reflects a three-way interaction between touch, proprioception, and vision.

Moreover, as discussed above, body image is shifted by the illusion, which modulates the perceived similarity between the incorporated hand and the real one (Longo et al., 2009), thus suggesting that ownership leads to changes in perceived physical similarity.

Alterations in body representation do not stop to the shifts in body representations. The feeling of ownership over the rubber hand dictates changes in the way one's real hand is processed. This is valid both at the introspective and physiological levels. Indeed, after RHI, participants felt like their hand had disappeared (Longo et al., 2008), as if the artificial limb had been incorporated into their body representation while replacing the organic equivalent. Simultaneously, this introspective change correlates to a physiological alteration. Shifting the sense of ownership from the real hand to the fake one corresponds to a significant alteration in the homeostatic regulation of the real hand (Moseley et al., 2008). Specifically, the skin temperature of the real hand decreased when participants experienced RHI. The more vivid the illusion, the lower the temperature of the real hand decreased. A change in conscious experience of ownership had direct consequences on a homeostatic and physiological level. Further evidence of the impact of the RHI on the physiology of the body comes from the immune system. As a matter of fact, histamine reactivity increased in the "rejected" arm during the illusion, implying that the interoceptive system begins to renounce and disown the real hand in favor of the prosthetic equivalent (Barnsley et al., 2011). Overall, this evidence depicts the characteristics of what binds a body to the feeling of owning that body. Bodily self and self-awareness are heavily based upon this feeling of ownership (Tsakiris, 2017), which is the result of a multisensory integration between vision, proprioception, and touch. The repercussions of this sense of ownership are both on conscious, unconscious, and physiological levels, highlighting the connection between the sense of self and the body. However, the rubber hand illusion illustrates perfectly how this feeling is fragile and liable to be confused, altered, and deceived. Under the effect of the illusion, the artificial limb is swiftly incorporated, thus producing the feeling of ownership.

1.1.7: Embodiment

There's an ever-growing number of instances where external objects are assimilated into the representation of the body. The rubber hand illusion is not the only instance eliciting a sense of ownership, which can be felt towards allograft, prostheses, virtual avatars and tools, etc. (Cole et al., 2009; Dubernard et al., 2003; Maravita & Iriki, 2004; Murray, 2004). What is felt as a part of the body can be in flesh and blood, in rubber, in metal, or even virtual. It may be anatomically shaped or not.

How can anyone feel a sense of ownership towards objects so different and, more importantly, located outside of bodily borders?

The answer is embodiment. Notwithstanding the lack of a common agreement on the relation between ownership and embodiment, many agree to address the former as a sub-component of the latter (de Vignemont, 2011; Giummarra et al., 2008; Longo et al., 2008). De Vignemont (2011) defines embodiment as "a specific type of information, whereas the sense of embodiment corresponds to the associated phenomenology, which includes the feeling of body ownership". From the same extract: "Embodiment: E is embodied if and only if properties of E are processed in the same way as the properties of one's body". In other words, an object is embodied if it shares some properties with a body part or with the body.

Spatial	If E is taken into account by the representation of the body space, by replacing a missing body part, by adding a body part, or by stretching an existing body part, If one is able to localize bodily sensations in E, If the location of E within the external frame is processed in the same way as the location of a part of one's body, If the space surrounding E is processed as peripersonal space,	**Then E is embodied**
Motor	If one feels that E directly obeys one's will, If one feels that a part of one's body is moving when E is moving, If E is taken into account as an effector by the motor system in action planning,	
Affective	If E is protected from hazardous situations, If one reacts in the same way when E is threatened or hurt and when a part of one's body is threatened or hurt,	

Figure 5: Properties of Embodiment (de Vignemont, 2011)

Some of these properties were already discussed, such as the urge to protect the embodied object when threatened (Armel & Ramachandran, 2003). Subjectively, one feels that his/her body directly obeys his/her will and the body is experienced as it carries out actions successfully. Hence, if one feels that an object obeys one's commands, then the object is embodied (de Vignemont, 2011). Moreover, action awareness and sense of agency come with the experience that one's body is moving. If one feels that a part of one's body is moving when the object is moving accordingly, then the latter is embodied (Short & Ward, 2009).

Motor measures of embodiment involve tools, especially when used as an effector in action planning. In doing so, the motor system takes into account the properties of the tool, such as its size, its location, its posture, etc. As a case in point, Cardinali et al., (2009) illustrated that using a long mechanical tool to grasp objects altered the kinematics of successive free-hand grasping movements, as well as other non-trained movements like pointing. Furthermore, this effect insisted on an increase in the represented length of the arm. Indeed, after tool use, blindfolded participants localized touches delivered on the middle fingertip and the elbow of the same arm as if they were farther apart. In this case, embodiment caused an update not only in the body schema, due to the use of the tool. At the same time, the body model was also updated, since their representation of the size of the arm was altered.

An additional instance where an object can be embodied is when it is integrated into the representation of the body space, by replacing a missing body part, by adding a body part, or by stretching an existing body part (Berti & Frassinetti, 2000). This last possibility will be discussed later, along with another property of embodiment: processing the space surrounding the embodied object as peripersonal space.

Numerous instances allow the embodiment of external items. However, only when all the properties of an object are processed in the same way as one's own body, the object is fully embodied. Consequently, only one's own biological limbs are perfectly embodied (de Vignemont, 2011). Nevertheless, embodied objects can induce changes in one's body representation even if they do not match all its properties. The nature of these alterations is often based upon the functional role of the embodiment, or rather, the reason why something is embodied.

De Vignemont (2011) suggests a distinction between perceptual embodiment and motor embodiment. An object is perceptually embodied if it is processed in the same way as a part of one's body for perceptual tasks. Vice versa, motor embodiment arises when an object is processed as if it were a part of one's body during action. The distinction between the two corresponds to specific types of body representations. Indeed, motor embodiment modulates the dynamic aspects of body representations, alias the body schema, by adding the external object's information into the sensorimotor schema, such as displayed in Cardinali et al. (2009). During purposeful, prolonged use, tools are felt to become a part or extension of the arm and are embodied within the body schema (Berti & Frassinetti, 2000; Gallagher & Cole, 1995; Maravita & Iriki, 2004) such that movement at the tip of the tool are perceived and processed as if they were displacement of the hand itself (Yamamoto & Kitazawa, 2001).

Conversely, the perceptual embodiment consists of representing the object within the body image, thus affecting aspects such as similarity towards the rubber hand (Longo et al., 2009).

Both types of embodiment are associated whenever it comes to one's biological body, but it is not always the case for tools, prostheses, or rubber hands. For example, the location of the rubber hand is perceptually embodied, but not motorically, since the artificial hand can't move (Kammers et al., 2009). This is not the case for the mirror box illusion, as will be shown further on. Overall, from embodiment stems a myriad of possible interactions with the world that could never fit in this discussion (Ziemke, 2003). Nevertheless, this narrow definition of the construct allows to understand how one can feel an external object as if it were part of its own body. Embodiment penetrates both at a perceptual and motor level, modulating body representation by changing the way one perceives his/her own body and allowing the use of prostheses and tools as if they were a constitutive part of the body.

1.1.8: The Complexity of Somatoperception

To sum up, somatoperception involves an integrated, online percept of the current state of the body, based on calibrating the available multisensory input with a pre-existing representation. Longo's classification provides a framework to delineate the various facets of body representation, highlighting how the perception of the body is shaped by both sensory input and cognitive interpretation. Body representations contribute to defining the sense of awareness of one's own body as well as of external objects. As stated before, there is no common agreement in research about body representations in general. This is also due to the many possible dissociations and overlaps between representations. Nevertheless, it is fundamental to establish these reference points, to allow further understanding on this topic.

1.2: Representation of Space Around the Body

Body representations play a fundamental role in taking action. As a case in point, body schema encompasses a dynamic representation of the body, which is essential information for guiding the body through movement. While somatosensory modality monitors the physical contact between our body and external objects, visual perception promptly acquires information about events occurring in external space, before any impact with the body. The link between these two sensory modalities is critical when an individual is called to react to external stimuli. Via multisensory integration, an individual can efficiently navigate the environment and successfully interact with it (Macaluso & Maravita, 2010).

The interplay between vision, body, and its posture in space advocates for a strict link entwining somatoperception and body representations to the perceptual space adjacent to the body, the so-called peripersonal space (Graziano et al., 1997; Rizzolatti et al., 1997).

1.2.1: Peripersonal Space

Peripersonal space (PPS) defines the region of space immediately surrounding one's body, in which objects can be grasped and manipulated. By contrast, extrapersonal space refers to the space beyond direct action, in which exploratory eye movements occur. Peripersonal space representation is pivotal in the sensory guidance of motor behaviour, allowing interaction with objects and people near us (Di Pellegrino & Làdavas, 2015). At the same time, whenever an object is coming towards the individual, defense or avoidance are actions possible thanks to these kinds of representation.

Neurophysiological studies, such as Rizzolatti's renowned work (Rizzolatti et al., 1981), revealed discrete processing of PPS in single-cell recordings. They examined neurons from the ventral intraparietal area (VIP), specifically the F4 area of macaque monkeys. A large proportion of neurons in this area were found to be bimodal, discharging in response to both tactile and visual stimuli. Critically, unlike classical visual neurons, F4 neurons fired poorly to light stimuli located afar. On the contrary, they were effectively triggered by real three-dimensional objects moving near the animal. In other words, these bimodal neurons only fired when something entered the monkey's reach. An additional finding from Graziano et al. (1997) highlights the close connection between the visual and the tactile reception field of these bimodal neurons. In this study, a monkey was trained to fixate one of three lights, while its arm was strapped to a holder and positioned on the left or the right side. A series of visual stimuli approached the monkey. The trajectories of these stimuli were multiple: toward, away, left, right, up, and down. For many neurons, both the visual and tactile responses were found to be directionally selective. Specifically, for 70% of these bimodal neurons with a tactile response on the arm, the visual receptive field (RF) moved when the arm was moved. After the passive displacement of the monkey's arm from right to left or vice versa, there was a shift in the location of the visual RF, that did not correspond to eye or head movement. Indeed, changes in fixation points did not elicit an equivalent change in fire rates of these neurons. Instead, they fired only when a stimulus was approaching the arm, whether it was positioned on the right or the left. Such findings advocate for an 'anchorage' in the bipolar neurons of F4 areas between their visual receptive field and their tactile reception field. In conclusion, the visual receptive fields move together with the limb, disregarding eye or head movement.

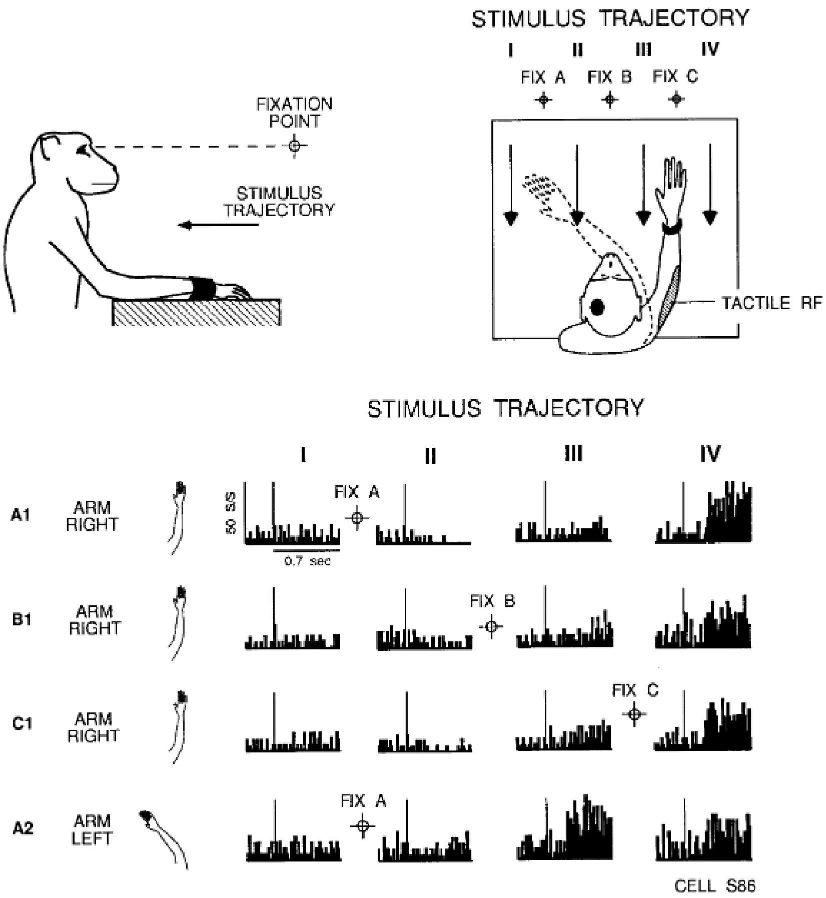

Figure 6: Visual Stimuli Approaching the Body Activate Bimodal Neurons in Monkeys (Graziano et al., 1997)

Top: experimental paradigm for testing the effect of arm position. On each trial the animal fixated 1 of 3 lights spaced 20° apart (FIX A, FIX B, or FIX C) and the stimulus was advanced along 1 of 4 trajectories (I–IV). The arm was fixed in 1 of 2 positions. Trajectories and monkey are drawn to the same scale. Stippling: tactile receptive field (RF) of the cell whose responses are illustrated at bottom. Bottom: histograms of neuronal activity, summed over 10 trials, as a function of eye position (A–C), stimulus position (I–IV), and arm position (to the right in rows A1, B1, and C1, and to the left in row A2). Vertical lines: stimulus onset. When the arm was fixed to the right, the neuron responded best to the rightmost stimulus trajectory (IV), whether the eye looked to the left (as in row A1), to the centre (as in row B1), or to the right (as in row C1). However, when the arm was fixed to the left (row A2), the neuron responded best to stimulus trajectory III. That is, the visual receptive field moved toward the left with the tactile receptive field. Results for conditions B2 and C2, not shown, were similar.

Therefore, the functional properties of these bimodal neurons can be summarized as follows: the visual receptive fields are closely corresponding to tactile receptive fields and operate to some degree in body-part-centred coordinates. Indeed, the visual receptive fields move along with the body part and not with the eye. Furthermore, the extent of the visual RFs is typically restricted to the space surrounding the body part. The last feature displayed is the strength of the visual response decreasing with distance from the body part. Altogether, these bimodal activation patterns strongly suggest the existence of a space within the monkey's range, in which tactile and visual information are integrated to interact with the proximal environment.

1.2.2: Peripersonal Space in Humans

Research has confirmed the presence of equivalent neurons in humans, sharing the same functional properties. A functional magnetic imaging (fMRI) study (Bremmer et al., 2001) highlighted the distribution of polymodal neurons. In other words, neurons that show polymodal directionally selective discharges, firing to moving visual, tactile, vestibular, and auditory stimuli. Subjects were presented with either a visual (large random dot pattern), tactile (airflow), or auditory (binaural beats) moving stimulus. Whenever stimuli were moving, regardless of their sensory modality, significant cortical activation was registered. Specifically, the fMRI displayed an activation pattern in the ventral intraparietal cortex, the ventral premotor cortex, and the lateral inferior postcentral cortex. No significant activation was recorded when static stimuli were presented. These findings thus strongly imply the existence of the human equivalent of bimodal neurons found in the VIP macaque area.

Additional evidence comes from fMRI recordings in the parietal face area (Sereno & Huang, 2006). Visually guided eating, biting, kissing, and avoiding objects moving towards the face require prompt, coordinated processing of spatial visual and somatosensory information to protect the face and the brain. Sereno and colleagues mapped the organization of a multisensory parietal face area in humans, by acquiring fMRI images while varying the polar angle of facial air puffs and close-up visual stimuli. In doing so, they found aligned maps of tactile and near-face visual stimuli in the superior part of the postcentral sulcus. Critically, this work suggests that the aligned somatosensory and visual maps code the location of visual stimuli taking the face as a reference, not the retina.

Neuroimaging findings are not the only type of evidence advocating for multimodal representation of the peripersonal space in humans. Indeed, neuropsychological investigations show the existence of intersensory integrative systems representing space through the coding of both visual and tactile events. Patients suffering from unilateral brain lesions (right hemisphere) may not be able to report a single stimulus presented on the controlesional side when a competing stimulus is simultaneously shown on the ipsilesional side. As a case in point, if patients were touched in both hands at the same time, they were able to detect only the left side stimulus. This occurs even though they can report either stimulus when presented alone. The aforementioned phenomenon is called extinction (Bender, 1952) and it is attributed to the unbalanced competition between concurrent targets for access to limited attentional resources (Di Pellegrino et al., 1997). Usually, the experimental settings designed to elicit extinction involve stimuli that are presented in the same sensory modality. However, if peripersonal space really is a bimodal representation, extinction phenomena should arise even with stimuli from both sensory modalities. Ten participants with comparable unilateral brain lesions (on the right hemisphere) were tested with this rationale (Làdavas et al., 1998). A visual stimulus presented near the patient's ipsilesional hand (i. e. visual peripersonal space) inhibited the processing of a tactile stimulus simultaneously delivered on the controlesional hand, thus showing a cross-modal visuo-tactile extinction. The impairment in the detection of the contralesional stimuli was comparable to the tactile extinction presented above. Critically, when visual stimuli were presented afar from the hand, or in other words in the extrapersonal space, modulation decreased and detection of the tactile stimuli improved. The cross-modal extinction was far stronger for visual stimuli within peripersonal space.

In addition, to examine the spatial coordinates used to code peripersonal space, a patient with tactile extinction was asked to cross the hands such that the left hand was in the right hemispace and vice versa (Di Pellegrino et al., 1997). A visual stimulus presented near the right hand (in the left space) extinguished tactile stimuli applied to the left hand (in the right hemispace). Thus, the cross-modal visuo-tactile extinction was not modulated by the position of the hands in space. On the contrary, it seems that when the hand is moved, the visual peripersonal space remains anchored to the hand and therefore moves with it. These findings together advocate for the existence of a visual peripersonal space centered on the hand (peri-hand space) in humans and its modulatory effects on tactile stimulus detection. The strength of this modulation is proportional to the stimuli's distance from the body part. Therefore, peripersonal space in humans shares the same properties displayed in the previously discussed studies about bimodal neurons in macaque monkeys.

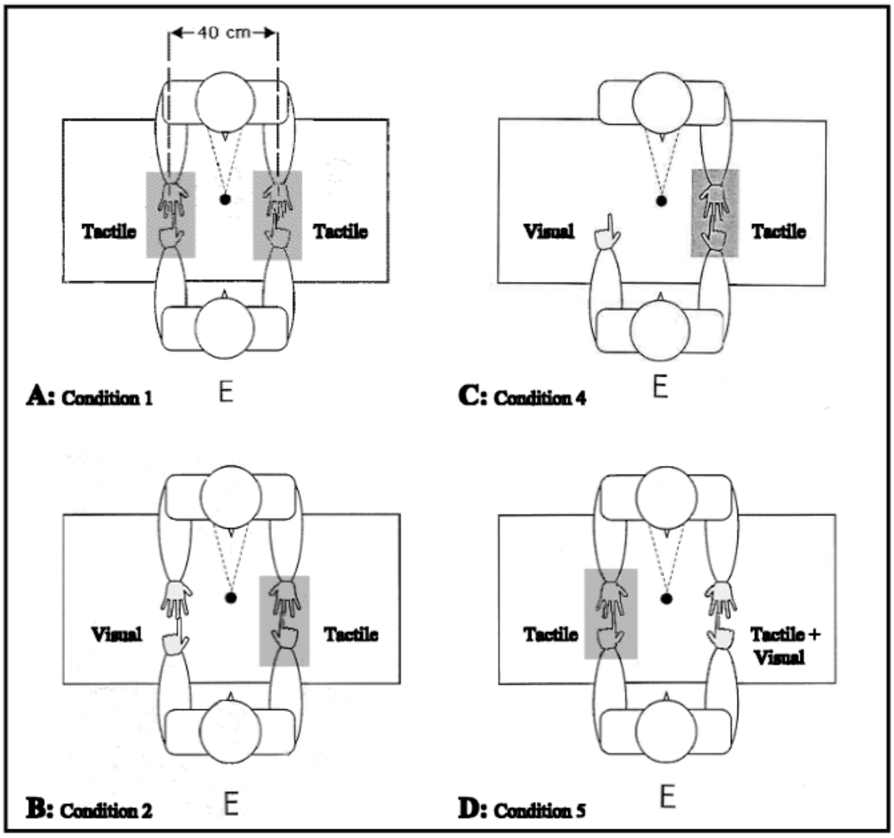

Figure 7: Experimental Setting in the Cross-Modal Extinction Paradigm

(Làdavas et al., 1998)

The patient was seated at a table in front of the experimenter (E). Patient's hands rested on the table surface and were occluded from vision using cardboard shields (grey rectangles). The filled circle on the table indicated the point of fixation. "Visual" and "Tactile" refer to the type of stimuli applied by the experimenter in the different conditions.

1.2.3: Vision and Proprioception and Peripersonal Space

A sine qua non condition for the occurrence of space-specific cross-modal effects such as extinction is the following: integrating the spatial distance of visual objects with a given sector of the patient's body (Di Pellegrino et al., 1997). Whenever a person wants to grab an object, he/she must estimate the distance of their target, as well as the reach of the operating body part. But how does the multisensory system estimate the distance between the hands and nearby visual objects? In humans one possibility is by combining proprioception and vision (van Beers et al., 1999). Indeed, responses based only on proprioception are much weaker than the ones evoked when the vision of the arm is also allowed (Graziano, 1999).

Hence the question: is visual information regarding the hand more relevant than its proprioceptive information for the representation of peripersonal space? To find an answer, the same cross-modal extinction paradigm was utilized, except for the fact that patients were sorted into two groups, one in which they could see their hands and the other in which they couldn't (Làdavas et al., 2000). Patients' performance indicated that controlesional tactile perception improved when the visual stimulus was presented near the right hand while it was hidden. Conversely, extinction rates were higher when participants could see their hands. Whether the visual stimulus was presented near or far from the patients' ipsilesional hand, if patients couldn't see the contralesional limb, the difference in cross-modal extinction was non-significant. Even though proprioceptive feedback was unchanged across conditions, preventing participants from seeing their controlesional hand caused a considerable difference in performance. This advocates for a moderate, if not limited, contribution of proprioception to the representation of the hand-centred visual peripersonal space. Therefore, vision of hand position in space has a major impact in coding the distance of visual stimuli from someone's hands. The finding goes accordingly with the notion that visual information usually overcomes low spatial resolution senses like proprioception (Rock & Victor, 1964; Warren & Cleaves, 1971).

Surprisingly, visual information about the hand, besides being necessary, can also be sufficient for the integrated processing of visuo-tactile input in peri-personal space (Farnè, 2000). Once again, right brain-damaged patients with left tactile extinction were tested with a cross-modal extinction paradigm. This time, the near visual stimuli were presented in the proximity of the patients' real hand or near a rubber hand. For the fake hand condition, participants held their arm behind their back and the artificial hand was placed so that it could either be aligned or misaligned with the patients' ipsilesional shoulder. Patients showed cross-modal visuo-tactile extinction not only when visual stimuli were presented near the real hand, as in precedent studies, but also in the rubber hand condition. Critically, the effect was evident only when the fake hand was positioned in a plausible orientation, according to the participants' shoulder. In contrast, cross-modal extinction was strongly reduced when the rubber hand's posture was implausible. Hence, proprioceptive input comes in play when its cues are extremely discrepant with visual information. Normally, both visual stimuli approaching the hand and the hand itself are under visual control, and the felt position of the hand is congruent with its seen position. In Bayesian terms, since vision and proprioception are normally associated, the probability of the two being dissociated is small, even when they deliver conflicting information. Consequently, the deception caused by the RHI reflects a sort of impenetrability of the integrated visual-tactile system to discrepant information provided by proprioception. Only if the rubber hand is positioned in an impossible posture with regards to the participant's body, then the system is no longer deceived, and the integrated processing of visuo-tactile inputs in peripersonal space is impeded. This study sheds additional evidence on the dominance of vision and touch over proprioception in defining peripersonal space. The system coding peripersonal space can be 'deceived' by the vision of a fake hand, provided that its appearance looks plausible to the subject's body. Further discussion on this topic will follow.

1.3: Interaction Between Body Representations and Spatial Representations

In a normal situation, vision, touch, and proprioception convey coherent information that binds peripersonal space to the area surrounding the body. Indeed, the radius of peripersonal space is usually limited to the body's reach, which is the portion of space with which the person can interact (Di Pellegrino & Làdavas, 2015). However, action is not restrained by the body's anatomical reach if tools are taken into consideration. Through the use of utensils, one can access a wider portion of the surrounding space. Does this translate into an extension of peripersonal space?

1.3.1: Expansion in Peripersonal Space

A neurophysiological study on macaque monkeys suggests so (Iriki et al., 1996). They studied bimodal neurons in the intraparietal sulcus, which naturally share the functional properties with the ones in the articles above (Graziano et al., 1997; Rizzolatti et al., 1981). A re-coding of relatively far visual stimuli as nearer ones has been observed in monkeys' single cells, after extensive use of a tool. In this study, a rake-shaped tool was held and used by macaques to attain otherwise out-of-reach food pellets, thus extending the hand's reachable space. The monkeys were trained and accustomed to the use of the rake in retrieving distant food. A few minutes of tool use induced an expansion of visual receptive fields of bimodal neurons recorded in the parietal cortex. It was as if the monkeys considered the rake as a prolongment of their hands. The utensil had been incorporated into the hand's peripersonal space representation, thus expanding the latter. Critically, the extension of the visual RFs in bimodal cells returned to normal after a short rest, even if monkeys were still holding the rake. No modification whatsoever followed when monkeys were just passively holding the utensil. Therefore, the tool-related expansion of the receptive fields was strictly dependent on the active use of the rake in retrieving distant objects.

Similar peri-hand space expansion was also found in humans (Berti & Frassinetti, 2000). This case study revolved around a patient named P. P.. After a lesion to the right hemisphere, she was affected by visual neglect, a condition that prevents the processing and the exploration of the space contralateral to the brain lesion. Impaired coding of near space can coexist with adequate representation of far space (Halligan & Marshall, 1991). At the same time, the opposite dissociation is also possible, which is a type of neglect limited to far space (Vuilleumier et al., 1998). Specifically, P. P. couldn't detect stimuli in her left visual hemifield, but only when said stimuli were in her peripersonal space. To elicit such a deficit, she was asked to perform a line bisection test. A series of lines on white A3 sheets were positioned in her proximity (50 cm) or at a distance of approximately 100 cm (far space). For the near stimuli, P. P. could either reach with her right finger or point by using a projection lightpen. Instead, for the far stimuli, she could reach the midline using a 100 cm stick or employing the same projection lightpen. P. P.'s performance was aligned with her near-space neglect diagnosis. Whether by pointing or by reaching, she showed a rightward displacement for near stimuli, bisecting the lines on their right side. On the other hand, in the far condition she correctly bisected the lines, but only when she was using the lightpen projector. Indeed, while reaching the middle of the line with the stick, she showed the same rightward displacement as she did with the near stimuli. This inconsistency in P. P.'s performance can be explained by considering how body representations work.

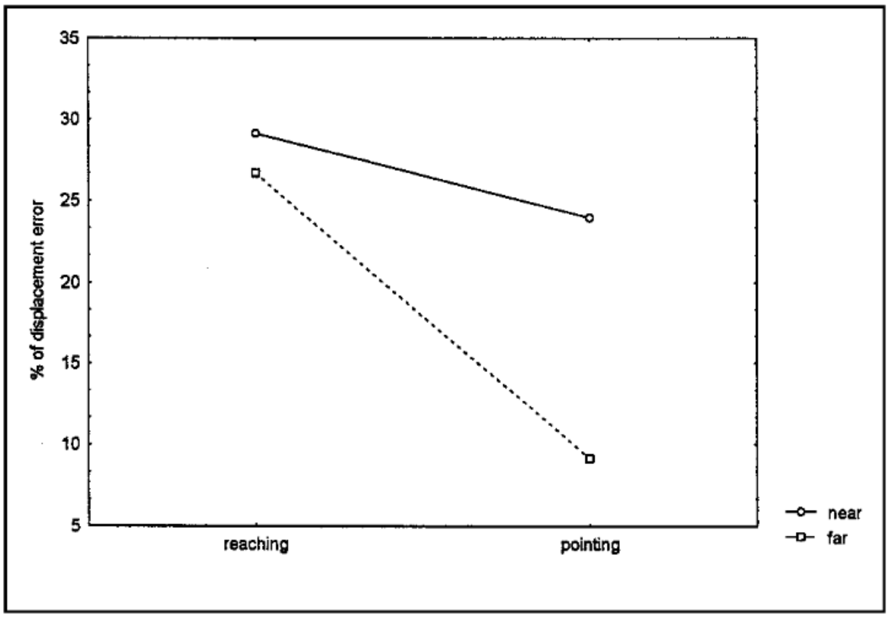

Figure 8: Percentage of Rightward Displacement as a Function of Space and Modality (Berti & Frassinetti, 2000)

1.3.2: Embodiment of Tools and Peripersonal Space

Similarly to macaque monkeys (Iriki et al., 1996), tool use increased P. P.'s range of action. As previously illustrated, tools are effectively embodied and integrated into the body schema during purposeful use (Gallagher, 2000; Maravita & Iriki, 2004; Yamamoto & Kitazawa, 2001). To be specific, employing a long stick can induce changes in the body schema, as the latter accounts for the increase in the reach and swiftly balances out the output needed for action. At the same time, tool use dictates morphological variations in the body schema as well as in the body model, so that the stick is considered as a prolongment of the arm (Cardinali et al., 2009). Consequently, visual stimuli that are close to the tip of the stick are processed as if they were near the extremity of the arm. In other words, by being embodied, the tool is represented as a part of the patient's body. This causes the tool to be included in her peripersonal space, simultaneously entailing the expansion of the near space and the change in P. P.'s performance. A "peri-tool" space implies that stimuli that were far had become near, crossing boundaries between extrapersonal and peripersonal space and ultimately eliciting near-space neglect for objects outside P. P's anatomical range. Overall, these findings display another functional property of peripersonal space representation: its plasticity. Rather than a fixed distance, peripersonal space representation seems to dynamically change with one's possibility to act on the environment. Using a tool allows the agent to interact with a larger portion of the surrounding space, and therefore its peripersonal space expands.

1.3.3: Embodiment and Peripersonal Space

At the same time, a change in body representation, due to the embodiment of the tool, corresponds to variations in spatial representation. Further evidence advocating for this significant modulation comes from the cross-modal extinction paradigm (Farnè, 2000). As already illustrated above, right-brain-damaged patients with tactile extinction displayed the same cross-modal extinction even when their real hand was replaced with a rubber hand. As a matter of fact, visual stimuli presented near the rubber hand replacing the contralesional limb were neglected as if they had been delivered near the real contralesional hand. In this case, the rubber hand embodiment led to the visual representation of the peripersonal space of a non-owned body part, as if it were the real hand. Critically, if the hand could not be embodied, peri-hand space didn't change, causing cross-modal extinction rates to be lower. This happened whenever the fake hand was positioned in an incompatible placement considering the patients' posture.

This behavioural evidence finds corresponding blood-oxygen-level-depedent (BOLD) activations in the fMRI study by Makin et al. (2007). The intraparietal sulcus (IPS) and the lateral occipital complex (LOC) were identified as the cortical areas responsible for the processing of the peri-hand space. Subsequently, sensory information about the hand was manipulated. At a visual level, dummy hands were employed, while the position of the real hand changed across conditions (proprioceptive information). At this point, a moving ball was presented. The object could either approach a far target or a target in the proximity of the thigh, where the participant's hand lay. In the dummy condition, the artificial hand replaced the biological limb, which was retracted to the participant's shoulder. During the dummy condition, participants displayed significant activation in the posterior IPS as well as in some regions within the LOC. The visual capture of the rubber hand (Pavani et al., 2000) elicited activations in the areas responsible for peri-hand space processing. Indeed, activation patterns were analogous to the ones in the real hand condition. Conflicting sensory information came from the rubber hand. Hence, visual stimuli overlapped proprioceptive ones, and the rubber hand was embodied. In turn, the embodiment caused a shift in the peri-hand space, from the biological limb to the artificial one, ultimately causing the activation of the intraparietal sulcus and the lateral occipital complex.

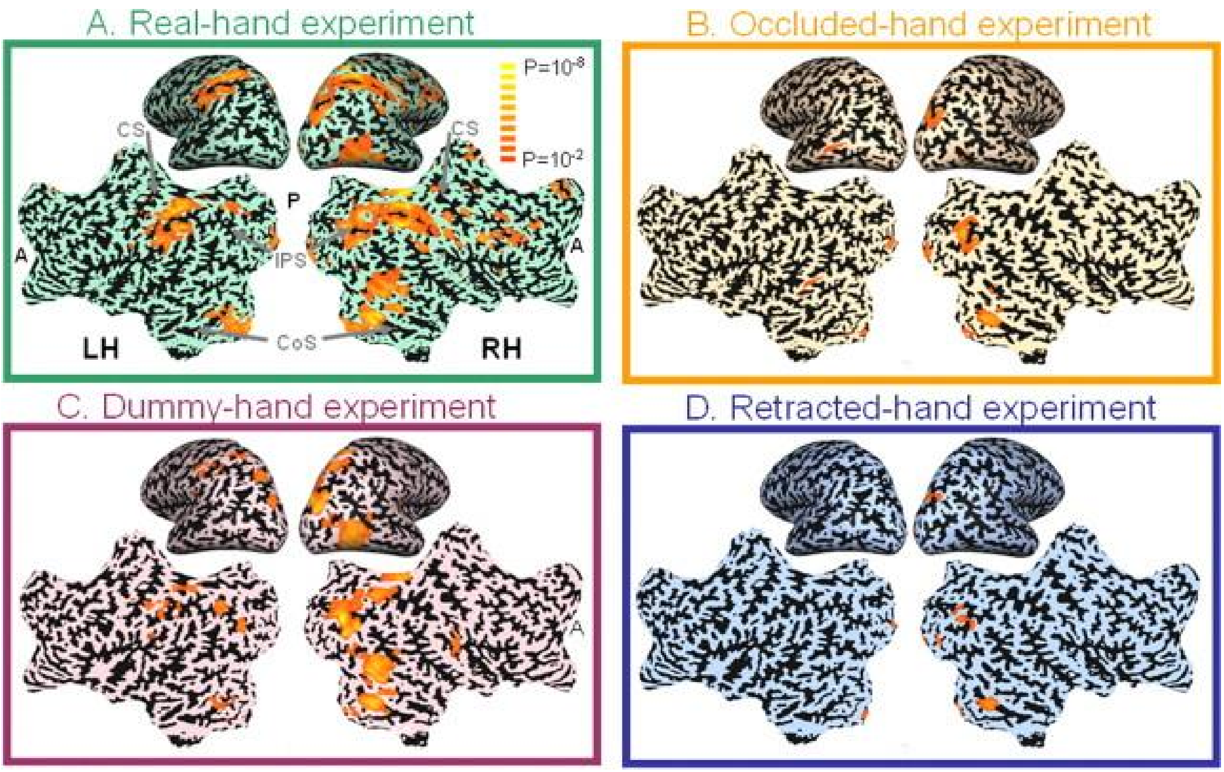

Figure 9: fMRI activation in the brain regions responsible for the representation of peri-hand space (Makin et al., 2007)

Group results: determining the relative contributions of visual and proprioceptive information to the hand schema. fMRI differential activation (whole brain corrected, $p < 0.05$) for near versus far stimuli on representative inflated and unfolded maps of the right hemisphere (RH) and left hemisphere (LH). Shown are the areas with preference for the ball approaching the near target: A) When next to the subject's hand. B) When the subject's hand was occluded from sight. C) When a dummy hand was placed at the same position as the occluded hand, while the subject's own hand was retracted. D) When the subject's hand was retracted away from the near target. The comparison between the activation preference in the different experiments enables identification of putative hand-related areas in the cortex, as well as the factors (visual or proprioceptive) governing the hand position-related representation. Note that the mere presence of the dummy hand modulated parietal areas in a similar way to the real hand. A, Anterior; P, posterior; CS, central sulcus; ColS, collateral sulcus.

1.3.4: Body Representations Can Modulate Spatial Representation

To sum up, peripersonal space is a spatial representation depicting the portion of space surrounding the body (Di Pellegrino & Làdavas, 2015). Multisensory information coming from vision, touch, and proprioception integrate to construct a coherent representation of the body and its proximity. Its extension is limited to what the body can reach. However, employing tools increases this reach and expands the peripersonal space (Berti & Frassinetti, 2000; Iriki et al., 1996; Maravita & Iriki, 2004). This is due to the embodiment of the tool during purposeful use, which is considered as an extension of the body. The same is valid for rubber hands and other objects that can be embodied (Farnè, 2000; Makin et al., 2007). The change in the body representations following embodiment manages to modulate the representation of peri-hand space.

Critically, the nature of this modulation is not limited to variations in the extension of peripersonal space. Indeed, after undergoing the rubber hand illusion, the perceived space around the body shifts in the opposite direction to the artificial hand (Ocklenburg et al., 2012). In this study, participants were presented with a rubber hand illusion. In this version, as in Botvinick & Cohen, (1998), the dummy hand was positioned in the same orientation and parallel to the real hand, so that the artificial one was disposed coherently with the participant's body posture. This way, the real hand lay further away from the body. Conversely, the rubber hand was closer to the body midline. Under the effect of the illusion, the artificial hand was embodied. This led to a change in the sense of location of the real hand: the perceived location of the participant's own hand drifted towards the rubber hand. This phenomenon is called proprioceptive drift. The integration of the artificial limb into the body model shifted the body midline, since the rubber hand was closer to it compared to the real hand. Thus, the subjective body midline was perceived further away from the real body midline, and closer to the opposite hand. The impact of the proprioceptive drift on the peripersonal space was investigated via a line bisection test. In this task, neurologically normal subjects present a leftward bisection error ascribable to pseudoneglect (Jewell & McCourt, 2000). This is attributable to hemispheric asymmetries in the allocation of spatial attention (Zago et al., 2017). After undergoing left RHI, participants' pseudoneglect was significantly reduced and the leftward bias was weaker. This was especially true for high responders, or in other words, people who experienced the illusion as very vivid. The embodiment of the left rubber hand and the consequent proprioceptive drift shifted their subjective body midline to the right. As a result, stimuli in space were also shifted rightwards. Ultimately, this led to a reduction of the leftward bias in the line bisection test. The same did not apply when the rubber hand illusion was administered on the right hand. Indeed, there was no significant variation in participants' performance when comparing before and after the illusion. Changes in the body representation determine variations in the way one perceives the surrounding space. Overall, the evidence up to this point advocates for a significant impact of body representation on spatial representation. The extension of this modulation does not stop at peri-hand space modifications. Rather, body representations affect the way one perceives space as a whole.

1.4: The Study

The evidence gathered so far suggests a significant modulation between body representations and spatial representations. Body representations are a multi-faceted ensemble that plays a crucial role in action as well as in self-awareness. Given their plasticity, body representations are susceptible to change, as illustrated in many instances discussed above. Specifically, the possibility of embodying even external objects poses questions on the bodily self as well as on the ability of the body representations to adapt and interact with exteroceptive stimuli. The latter is a particular feature that shows profound resonance on peripersonal space representation. Variations in the representation of the body imply an equivalent change in the representation of the space surrounding the body. Therefore, whenever an external object is embodied, peripersonal space accounts for the addition and extends to the object. This finding would be quite exceptional alone, however, the correspondence between body representation and peripersonal space displays further implications. One of which is the way the space surrounding the body is impacted as a whole by changes in body representation. The shift in perceived space displayed in Ocklenburg et al. (2012) advocates for such modulation. A change in the subjective body midline is caused by the embodiment of a rubber hand. The effects of this proprioceptive drift imply a shift in the perceived space important enough to modulate pseudoneglect in neurologically normal patients. Indeed, this physiological leftward bias is counterbalanced by a rightward reposition in the perceived space, ultimately leading to a change in line bisection task performance. As a matter of fact, participants under the effect of the rubber hand illusion bisected more rightwards after being subjected to the rubber hand illusion.

This work aims to replicate such findings, addressing the modulation of pseudoneglect and on spatial representation exerted by body representation changes.

1.4.1: The Mirror Box Illusion

Contrary to Ocklenburg et al. (2012), this experimentation was conducted using the mirror box illusion (Medina et al., 2015; Ramachandran & Rogers-Ramachandran, 1996). There are three main reasons for such choice. First and foremost, as mentioned above, the rubber hand illusion does not include proprioceptive feedback. Since the rubber hand is an inanimate object, it is impossible to integrate kinaesthetic information with touch and vision. Still, due to the dominance of vision over proprioception, a coherent representation of the rubber hand arises from the illusion (Farnè, 2000; Làdavas et al., 2000). Nevertheless, proprioceptive feedback is still taken into consideration, as displayed when the artificial hand's position is incompatible with the participant's body (Botvinick & Cohen, 1998). Given the multisensory nature of body representations, an illusion integrating perceptive feedback with motor feedback conveys coherent multimodal information, thus facilitating their integration. Mirror box illusion is superior in this aspect when compared to the rubber hand illusion. As a matter of fact, during the synchronous condition, the reflected hand mimics the movement of the hidden real hand. This way, the participant feels as if he/she is moving the hand seen in the mirror.

Secondly, the mirror box illusion portrays a photorealistic depiction of the hand, thus minimizing any difference between the participant's body and the non-veridical body part. Both perceptual and motor embodiment occur in this instance, rendering a more convincing illusion and increasing the feeling of ownership towards the rubber hand.

Lastly, future studies to the one presented in this thesis will further investigate the nature of the body-space relation by focusing on body temperature modulation. In his pioneering work, Moseley et al. (2008) illustrated a psychologically induced cooling of the hand caused by the illusory ownership of a rubber hand. However, subsequent attempts to replicate such findings couldn't manage to display a reliable cooling of the real hand during the rubber hand illusion (de Haan et al., 2017). Conversely, the mirror box illusion succeeded in replicating the body temperature modulation, showing a bilateral hand skin temperature drop following the modulation of body part ownership (Crivelli et al., 2021).

1.4.2: Aim of the Study and Hypothesis

These are the reasons why the mirror box illusion was preferred over the rubber hand, to extend the scope of the research on the link tying space and body. Specifically, this study aims to investigate the relationship between the embodiment of the mirrored hand and pseudoneglect. In order to do so, a group of healthy participants was asked to undergo the mirror box illusion. Before and after the illusion, they were invited to carry out a line bisection task as well as a task to localize the position of their hand inside the box. The latter was used to estimate the proprioceptive drift, while the former was used to investigate the effects of the procedure on pseudoneglect. Indeed, administering these tasks before and after the mirror box illusion allows to estimate respectively the change in the perceived location of the hand inside the box and the modulation on space perception caused by the illusion. Each of these three tasks was carried out on both hands. Additionally, a synchronous and an asynchronous condition were implemented in the experimental design. The sense of embodiment was examined via subjective reports through the use of a questionnaire.

The primary and most fundamental objective of this work is to replicate the mirror box illusion, thus eliciting the sense of embodiment over the non-veridical hand. At the same time, the procedure aims at shifting the perceived location of the hidden limb towards the mirror, ultimately causing the proprioceptive drift. In line with the evidence discussed above, the final goal of this study is to replicate the effect illustrated in Ocklenburg et al. (2012), where the embodiment of the external object modulates pseudoneglect.

As a measure of the effectiveness of the illusion, participants should report higher subjective feelings of ownership towards the mirrored hands in the synchronous condition, no matter the hand. The embodiment questionnaire should attest to such an increase. For what concerns the proprioceptive drift, in the localization task following synchronous stimulation participants are expected to point nearer to the mirror after the illusion. This would indicate that the embodiment of the mirrored hand shifted the perceived location of the real hand toward the artificial one. In the line bisection task after the synchronous stimulation, participants are expected to bisect with a bias towards the real hand, thus correcting pseudoneglect when the illusion is applied to the left hand. Significant differences are expected between hands, as laterality plays a role in reducing pseudoneglect. Specifically, the entity of the MBI modulation on the leftward bias should be higher when the illusion is applied to the participants' left hand.

Another prediction derives, such as the sense of embodiment correlating with the proprioceptive drift. Indeed, participants who subjectively report the illusion as more vivid should display a more significant proprioceptive drift, compared to participants who did not fall under the illusion.

Conversely, subjective reports of participants could advocate for the lack of illusion and therefore a scarce feeling of embodiment towards the mirrored hand. On the other hand, for the localization task, if the difference between pointing was to be non-significant, no shift would happen after the illusion. Provided that the illusion took place, the hypothesis of this study would be confuted by comparable performances in the line bisection test before and after the MBI. If participants were to bisect the line the same way as before the illusion, then the modulation of body representations on spatial representation would not take place. Furthermore, if the subjective sense of embodiment and proprioceptive drift were not bound together, significant proprioceptive drift could arise even without the feeling of ownership towards the mirrored hand. Lastly, proprioceptive drift could fail to modulate pseudoneglect. In this instance, participants with significant differences in the localization task would display a non-significant difference in the line bisection task.

2: MATERIALS AND METHOD

2.1: Participants

For this study, 36 participants were recruited (26 females, 10 males) ranging from 19 to 46 years of age [mean age (SD)=22.42 ±4.53 years]. The size of the sample was chosen by considering the number of participants employed for a previous, similar study (Crivelli et al., 2021). The recruitment of participants implemented the university newsletter; therefore, they all attended the University of Pavia at the time of the experimentation. Inclusion criteria were normal or corrected-to-normal hearing and sight and being right-handed. Such requisites were assessed with the Edinburgh Handedness Inventory. In addition, no previous history of mental or neurological illness was recorded. All participants were confirmed to be eligible for the study. Regarding the level of education, almost a third of the participants achieved a bachelor's degree (*n*=11, 0.297%), while the rest of the participants completed secondary education (*n*=26, 0.703%). Overall, participants reported 15.44±2.12 years of education. No participant was aware of either the aim or the hypothesis of this experimentation. The current study was approved by the local ethics committee (Department of Brain and Behavioural Sciences of the University of Pavia; protocol number 67/2020), with all experimental procedures being in agreement with the Declaration of Helsinki (BMJ 1991; 302: 1194). Participants gave their informed consent prior to taking part in the study, and they received compensation in the form of a quarter of a credit. After the completion of the experiment, both the aim and the rationale behind the study were illustrated to participants.

2.2: Materials

2.2.1: Mirror Box

To elicit the embodiment of an external object, the experimentation implemented a mirror box illusion. The box was a modified version of the MBI paradigm from Medina et al. (2015). It consisted of a 91.4 cm long and 40.6 cm wide flat wooden board. On top of the board, a wooden box was assembled. Half of it was hollow, allowing the participant to comfortably enter the box with their limb. The other half, which was the part of the box in the centre of the wooden board, was sealed with two acrylic mirrors positioned on its sides. A considerable space separated the two. Originally, Medina et al. (2015) used three variations of the distance separating the two mirrors. However, in the instance presented in this work, the study by Crivelli et al. (2021) was taken as a reference. Consequently, the gap between the two mirrors amounted to 15.24 cm, which is also the distance that elicited the stronger illusion of ownership in Medina et al. (2015). To limit visual information about the composition of the box, specifically about the gap between mirrors, a barber's cloak was draped upon the box before starting. Once everything was set, the cloak was adjusted on the participants, so that it could cover both the box and the limb inside it.

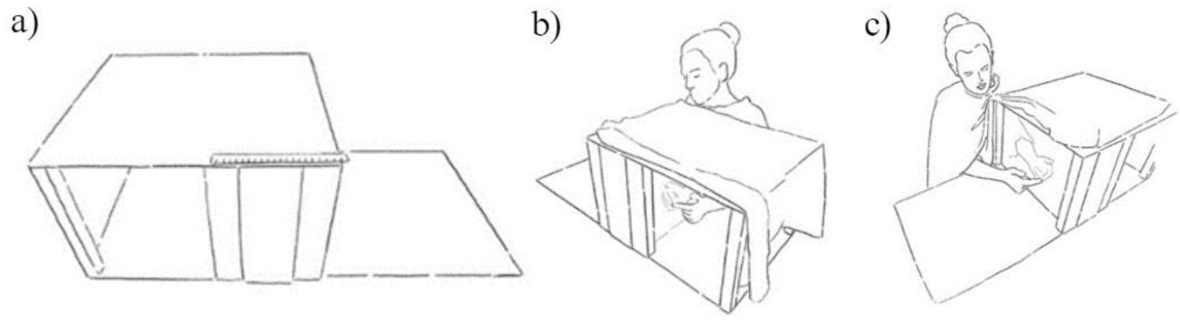

Figure 10: Illustration of the experimental set-up for Mirror Box Illusion (Crivelli et al., 2021)

The panel (a) shows the Mirror-Box viewed from the participant's perspective. Panels (b) and (c) illustrate a participant while performing the tapping movement. The subjects were instructed to perform the (synchronous or asynchronous) movement while looking at their right hand and its reflection in the mirror (c). During the entire procedure, the subjects' left hand was hidden from view by the upper surface of the box and a white cloak (b).

2.2.2: Webcam Mount

During the localization task there was a need to register the participant's subjective estimates of the position of the hand. To obtain such estimate, and consequently the participants' proprioceptive drift, a webcam was mounted on the ceiling above the set-up. The webcam provided a top view of the participants' arms and was used to take accurate measurements of the pointing movements made by the participants at the end of the MBI induction (Cataldo et al., 2024). The coordinates of each proprioceptive judgment were extracted by each picture through the ImageJ software (*ImageJ*, http://rsbweb.nih.gov/ij/). Subsequently, the edge of the box was used as a reference point to measure the difference between pointings. Ultimately, this difference was converted from pixels to centimeters.

2.2.3: Line Bisection

The line bisection task implemented in this study was comprised of two sets of 10 lines printed on two white sheets of A4 paper (21.0 x 29.7 cm). The horizontal set contained 10 horizontal lines positioned on the sheet, with lengths ranging from 6 cm to 15 cm. Every line was located at 1.3 cm from the others. Conversely, the vertical set contained 10 vertical lines positioned on the sheet, with lengths ranging from 4 cm to 16 cm. Each line was located at 2.6 cm from the others. One copy for each set was administered in every line bisection task.

2.2.4: Embodiment Questionnaire

The subjective report on the sense of embodiment was investigated through a questionnaire. This was originally taken from Medina et al. (2015), although it was translated to Italian and modified as in Crivelli et al. (2021). The questionnaire comprised of 8 statements. Participants responded to each item by reporting how much they agreed with that particular statement. Seven-point Likert scale options were possible, from being completely in disagreement to being completely in agreement. Among the items, a statement investigated the feeling of ownership towards the mirrored hand ("it felt as the hand in the mirror was my hand"). Being a subcomponent of the embodiment of the mirrored hand, the subjective feeling of ownership was taken as an indirect measure. Additionally, an item investigated subjective proprioceptive drift: "It felt as my hand was in the same position of the reflected hand", while another item focused on the sense of agency: "It felt like I was in control of the hand in the mirror". The de-afference of the biological hand and the consequent subjective feeling of dis-ownership were assessed with another item: "It felt as my hand went numb". Additionally, an item rated the pleasantness of the Mirror Box Illusion ("I found this experience pleasing"). A control item was also introduced, to ensure that participants weren't giving experimenter-complying responses ("It felt as if I couldn't tell where my real hand was").

2.2.5: State-Trait Anxiety Questionnaire

To address the possibility of anxiety-related interfering factors, participants were tested with the State-Trait Anxiety Inventory (STAI) (Carmin & L. Ownby, 2010; Spielberger, C. D., 1983). The STAI is a 40-item self-report scale that aims at assessing two dimensions of anxiety, which are state anxiety and trait anxiety. The former refers to anxiety about something happening, while the latter refers to personality levels of anxiety. Through the items in the inventory, feelings of apprehension, tension, nervousness, and worry are investigated. The STAI was handed out in its Italian version. None of the participants was excluded from the study, since none of them exceeded a STAI score of 60, indicating the threshold for interfering factors as mentioned above.

2.2.6: Handedness

One of the enrolment conditions of this study was to be right-handed. To ensure that all participants were suitable for experimentation, they carried out the Edinburgh Handedness Inventory (Oldfield, 1971). Consisting of ten items, the Oldfield Inventory asks the participant to indicate which hand they prefer to use for a list of daily actions. These range from writing to using a broom to lighting a match. With two supplementary items, the Inventory gathers information about the dominant eye and foot of the respondent. The Edinburgh Handedness Inventory is particularly useful in assessing the degree of departure from strong right-handedness, which participants tend to underestimate. No participant showed a significant deviation from right-handedness, for this reason, they were all able to participate to the study.

2.3: Procedure

After agreeing to the informed consent, participants went through all the experimental conditions in the same session.

At the start of the session, participants were asked to complete the State-Trait Anxiety Inventory and the Edinburgh Handedness Inventory. Once completed, participants were invited to the experimental setting. Before the start of the experiment, participants were asked to take off all rings, bracelets, and other items that could make each hand recognizable from the other. Due to the nature of the mirror box illusion, participants had to keep the same position for the duration of the trials. Consequently, they were encouraged to find a comfortable position, so that their body midline aligned with the mirror and their hand could easily enter the box. At this point, participants were asked to close their eyes and a cloak was positioned on them so that they were unable to see their arm inside the mirror box, or the box itself (which was covered in the meantime). Before being subjected to the MBI, participants were asked to carry out the line bisection task and the localization task. Afterwards, participants were asked to position their hands against the mirror aligning both index fingers on the surface. This was necessary to maximize the visuo-tactile match during the MBI. Subsequently, participants were instructed to focus their attention on the reflection of the hand outside the box, while tapping on the two mirrors according to the experimental condition (synchronous or asynchronous). During this task, the experimenter monitored the participants' hand movements. Once the tapping movement ended, participants were instructed to keep their hand inside the box attached to the mirror. Maintaining the hand inside the box still, participants carried out the line bisection task and the localization task a second time. At the end of the second task, participants were asked to fill in the Embodiment Questionnaire.

Before advancing to the subsequent experimental conditions, participants took a brief pause. This was done so that they could reacquire awareness of their biological limb and return to canonical body representations. Each participant underwent all experimental conditions, so that everyone repeated the process described above four times. Consequently, the mirror box illusion was administered both on the right and the left hand. The same goes for the synchronous/asynchronous tapping on the mirror.

2.4: Tasks

2.4.1: Line Bisection Task

Participants were instructed to use their right or left hand, depending on the condition. At the same time, they had to keep the other hand inside the box, attached to the mirror. Subsequently, using a pen, participants had to cut each line in half with a single mark. To be specific, they were asked to bisect the line without hesitation, in a ballistic fashion. Indications were given to mark the middle of the line, as close as possible to its centre. Moreover, they were advised not to skip any of the lines and to keep the sheet as still as possible. Once participants went through the vertical set, they proceeded to the horizontal one, or vice versa. The order of presentation of the two sets was balanced across the sample.

2.4.2: Localization Task

Participants were asked to attach both hands to each side of the mirror and to close their eyes. Starting from a resting position, in which the hand outside the box lay on the table, participants had to estimate the position of the hand inside the box. They did so by indicating on the upper surface of the box the point that corresponded to the perceived position of the hand. Participants had to repeat the task thrice before progressing to the next task. For each of these pointings, the experimenter recorded the position indicated by taking a picture of the operating hand. The pictures were shot by a webcam positioned above the box so that the frame contained the entirety of the cover of the box.

2.4.3: Mirror-Box Illusion

A cloak was draped upon both the participants and the box (which was hidden for the whole time) to limit visual information regarding the box and the participants' arm. Subsequently, participants inserted their right or left arm in the box depending on the experimental condition. At this point, participants were asked to align both index fingers on each surface of the mirror and the experimenter checked to see if they were aligned. Finally, participants were instructed to tap their left and right index fingers against the mirror while focusing on the reflection of the hand outside the box. During the whole process, the biological arm inside the box was hidden. In the synchronous condition, participants had to tap both fingers at a rhythm of 170 bpm, listening to a metronome. This frequency was the same used in Medina et al. (2015) and in Crivelli et al. (2021). Instead, in the asynchronous condition, participants had to tap the mirror at the same rhythm while alternating fingers with each beat. The movement lasted for 60 seconds, at the end of which, participants were instructed to keep the hand inside the box in place, before advancing to the next tasks.

Before and after each MBI administration, participants had to carry out the line bisection task and the proprioceptive task. This routine was designed to highlight the difference supposedly produced by the embodiment of the reflected hand as in Medina et al (2015) before and after the illusion was installed.

2.5: Statistical Analysis Plan

Being the most fundamental part of the experimental procedure, analysis began by assessing the effectiveness of the Mirror Box Illusion in inducing the feeling of ownership towards the mirrored hand. Additionally, proprioceptive drift was taken into consideration as an indirect effect of the MBI. Both the direct and indirect effects of the illusion were investigated. The former was measured via the items of the ownership questionnaire, as the subjective reports were considered a reliable form of insight into the effectiveness of the illusion. While the latter was estimated through the difference between participants' pointing before and after the MBI. Hence, participants' proprioceptive drift scores and their responses to the embodiment questionnaire were used as dependent variables of the two models.

For the localization task, a linear mixed model was implemented, with MBI (Synchronous, Asynchronous), Hand (Right, Left) and their interaction as fixed effects and random intercepts for participants. The dependent variable was the difference in pointing before and after the MBI. It was assessed via flat-lay photography thanks to the webcam mounted above the box. For each pointing the distance from the surface of the mirror was taken as a reference point. The pixel difference was then converted into millimetres.

The same linear mixed model was used for the embodiment questionnaire, with the addition of the Question Number (1 to 8) as fixed effect and its interaction with MBI (Synchronous, Asynchronous) and Hand (Right, Left)

Subsequently, statistical analysis focused on the line bisection task. Again, a linear mixed model was implemented, with MBI (synchronous, asynchronous), Hand (Right, Left) and Line Type (Horizontal and Vertical), and their interaction as fixed effects and random intercepts for participants. In this case, the dependent variable was the distance between the participants' bisected point of the line and its centre. This way, if a line was bisected rightward to its middle, it would result in a positive value, while a leftward bisection would be negative. In the same way, vertical lines bisected upwards with respect to their middle resulted in a positive value, while the opposite was true for bisection under their centre. The distance was measured in millimetres from the middle of the line.

To verify that the assumptions of the linear model were not violated, the residuals of the models were checked by visually examining Q–Q plots, to ensure that they were normally distributed. Data analysis was carried out using the software *Jamovi*. When necessary, pairwise comparisons were Holm-Bonferroni corrected.

3: RESULTS

3.1: Embodiment Questionnaire Subjective Reports

The analysis of the linear mixed model, using Question Score as a dependent variable and Question Number, Hand and MBI as fixed effects, revealed a significant main effect of Question Number ($F_{(7,\ 1240)} = 54{,}045;\ p < 0{,}001$). Indeed, participants reported different scores depending on the item of the questionnaire, as shown in Fig. 11.

Question Number	F	Num df	Den df	p
1	**52.5830**	**1.00**	**1240**	**< .001**
2	**28.9840**	**1.00**	**1240**	**< .001**
3	**42.7360**	**1.00**	**1240**	**< .001**
4	0.1930	1.00	1240	0.660
5	**4.3580**	**1.00**	**1240**	**0.037**
6	0.0750	1.00	1240	0.784
7	0.1090	1.00	1240	0.742
8	**31.3980**	**1.00**	**1240**	**< .001**

Figure 11: Main Effect of Question Number in the Embodiment Questionnaire

Moreover, the conditions of the MBI (i.e. Synchronous, Asynchronous) resulted in a significant effect ($F_{(1,\ 1240)} = 92{,}806;\ p < 0{,}001$), thus implying that participants responded differently after the synchronous condition compared to the asynchronous one. While the same was not true for the hand implemented in the procedure ($F_{(1,\ 1240)} = 0{,}730;\ p < 0{,}393$).

The results from the Embodiment questionnaire also revealed a significant MBI x Question Number interaction ($F_{(7,\ 1240)} = 9{,}662;\ p < 0{,}001$). Specifically, participants reported a higher score in the synchronous condition for the questionnaire items regarding the feeling of ownership (question number 1 and 3), the feeling of mislocalization (question n°8) and the feeling of agency (question n°2), as well as the positive affect resulting from the procedure (question n° 5). Therefore, participants reported increased subjective feelings of ownership, mislocalization of the real hand, as well as agency, after undergoing the Mirror Box Illusion. This interaction is visible in Fig. 12.

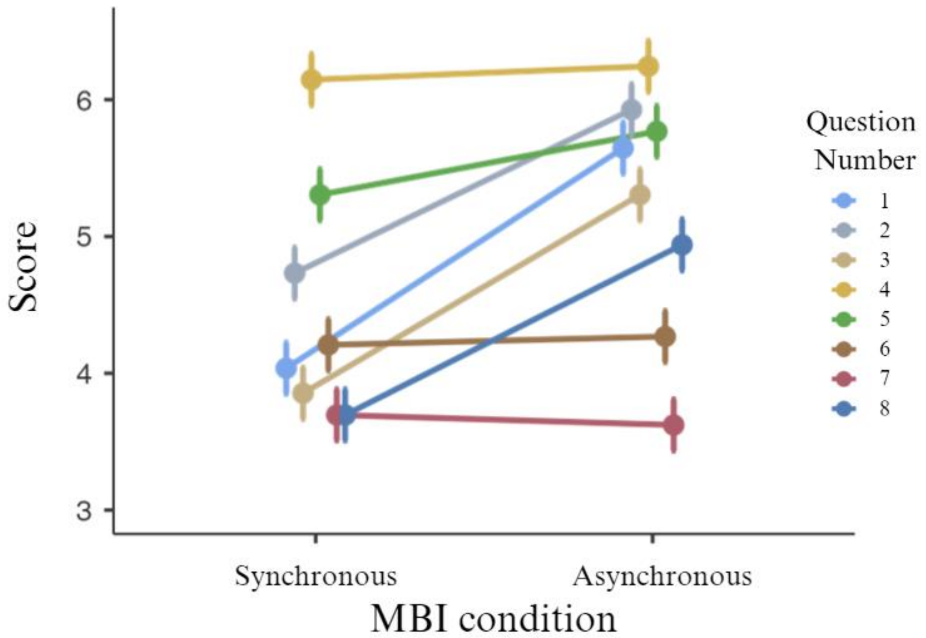

Figure 12: Interaction between Question Number and MBI condition in the Embodiment Questionnaire

3.2: Localization Task Pointings

For what concerns the analysis of the localization task, a linear mixed model was implemented, with Hand and MBI as fixed effects and the difference between pre- and post-MBI pointings as a dependent variable. This difference was measured in pixels from the pictures taken with the webcam and then converted to millimetres. A significant main effect of the MBI was found ($F_{(1, 444)} = 13,89; p < 0,001$), proving that pointings before and after the procedure were significantly different. Conversely, the effect of Hand was non-significant ($F_{(1, 444)} = 2,74; p = 0,099$) as the difference between pointings was comparable when the localization task was conducted with the left or with the right hand.

In addition, results indicated a significant interaction between the Hand and the MBI ($F_{(1, 444)} = 10,69; p = 0,001$). Indeed, a more significant difference in pointings resulted from the synchronous condition when the hand used to point was the right one ($F_{(1, 443)} = 24,672; p < 0,001$). Conversely, pointings carried out with the left hand did not present a significant difference across MBI conditions ($F_{(1, 444)} = 0,104; p = 0,748$). This does not imply that left-handed pointings resulted in non-significant differences. Overall, a significant difference between pre- and post-MBI pointings was found in the synchronous condition. Additionally, when the MBI was applied to the left hand (i.e. right pointing hand), the difference in pointings was significant even in the asynchronous condition. The interaction is displayed in Fig. 13.

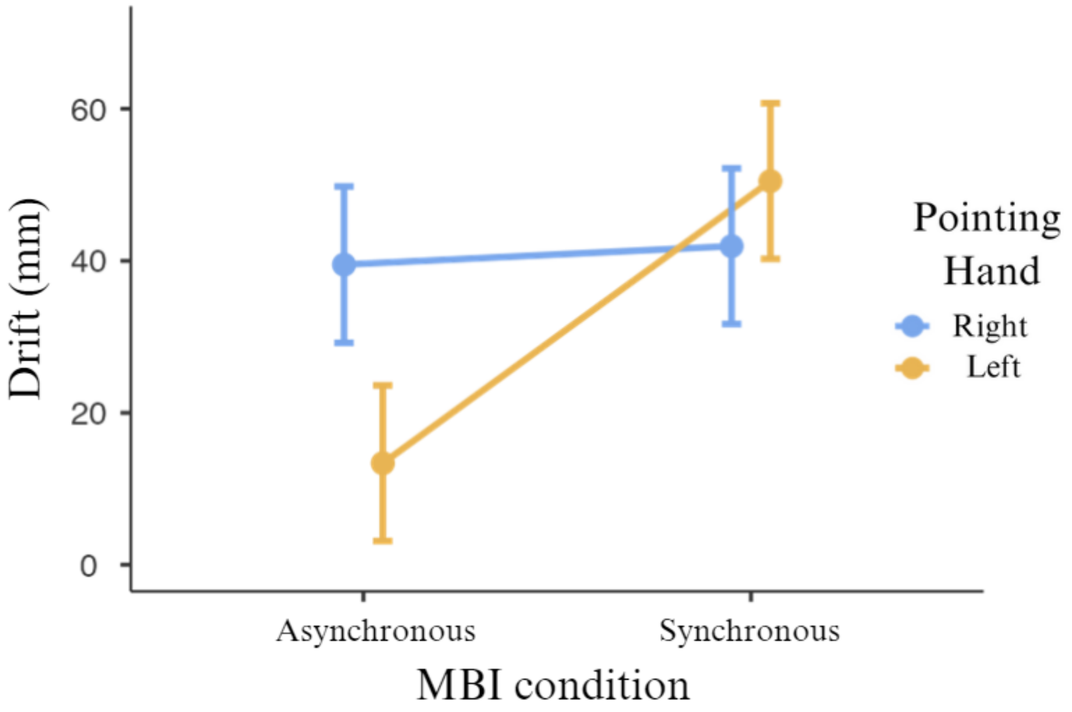

Figure 13: Interaction between hand and MBI condition on the localization task

3.3: Ownership Subjective Reports and Localization Task

A general linear model was implemented to investigate the relation between the feeling of ownership towards the mirrored hand elicited by the MBI, and the proprioceptive drift. The score in the feeling of ownership was taken as a fixed effect and random intercepts were assigned to participants. The dependent variable was the Drift, calculated from the difference in participants' performance between pre- and post-MBI localization tasks. A significant correlation between the feeling of ownership and the drift was detected (R^2 = 0,05; adjusted R^2 = 0,04).

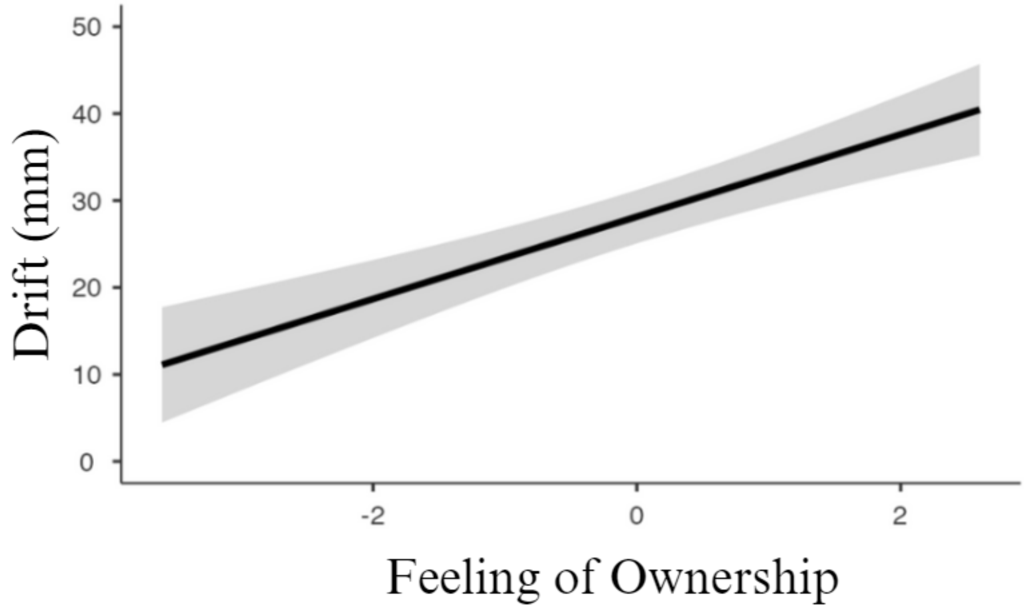

Figure 114: Correlation between Feeling of Ownership and Drift

An ANOVA showed that the model was statistically significant ($F_{(1, 12720)} = 8,39; p = 0.004$), proving that the score in the feeling of ownership item had a significant effect on the drift. The Kolmogorov-Smirnov test proved that the residuals' distribution was normal ($s = 0,06$; $p = 0,584$).

3.4: Line Bisection Task and Pseudoneglect

The analysis of the Line Bisection Task considered the difference from the centre of the line as the dependent variable. While Hand, Mirror and Line Type were taken as fixed effects, as well as their interaction. A main effect of the hand was present ($F_{(1, 40)} = 60,5; p < 0,001$), indicating that the performance in the bisection task differed across hands. Additionally, line type was responsible for a significant effect ($F_{(1, 40)} = 32,6; p < 0,001$), thus horizontal and vertical lines determined different performances. No significant effect was observed for the MBI ($F_{(1, 6432)} = 3,388; p = 0,066$). This result means that participants' performance in the line bisection task did not significantly change between the synchronous and asynchronous conditions.

Results also indicated a hand x line type interaction ($F_{(1,\ 6432)} = 467{,}902;\ p < 0{,}001$). A leftward bias was found in participants' performance, but only when the hand used to bisect lines was the left one. It is important to mention that this bias was present only for the horizontal lines. Indeed, no significant bias was observed when vertical lines were bisected with the left hand. Critically, when the line bisection task was carried out with the right hand, pseudoneglect was absent. An effective depiction of the interaction is visible in Fig. 15.

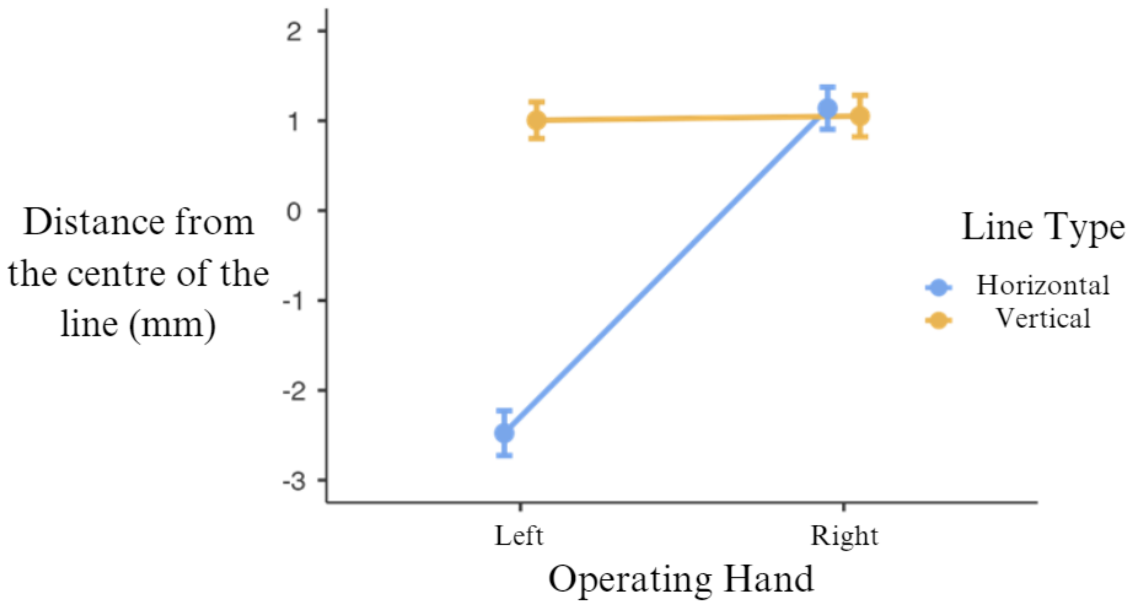

Figure 15: Interaction between Hand and Line Type in the Line Bisection Task

No further interaction was registered, as displayed in Fig. 16.

	F	Num df	Den df	p
Mirror	3.388	1	6432.0	0.066
Hand	60.500	1	40.0	< .001
Line Type	32.600	1	40.0	< .001
Mirror ✻ Hand	0.230	1	6432.0	0.632
Mirror ✻ Line Type	0.787	1	6432.0	0.375
Hand ✻ Line Type	467.902	1	6432.0	< .001
Mirror ✻ Hand ✻ Line Type	0.842	1	6432.0	0.359

Note. Satterthwaite method for degrees of freedom

Figure 16: Fixed Effect Omnibus tests for Line Bisection Task

4: DISCUSSION

Due to embodiment, external objects can be incorporated to initiate and accomplish finalized actions. This process dictates changes in the representations of the body that ultimately affect various cognitive domains. In this study, the spotlight was focused on the implications of these modifications on spatial representation. Embodiment repercussions on peripersonal space were discussed at length in the articles previously presented. This modulation does not stop at peripersonal space, as it can affect the representation of space as a whole (Ocklenburg et al., 2012). Indeed, the feeling of ownership towards a rubber hand can cause a shift in the subjective body midline towards the real limb. This implies a corresponding alteration in the perception of space, as demonstrated by the reduction of pseudoneglect. In light of this phenomenon, along with the evidence discussed above, the aim of this study was to replicate the modulation of spatial representation caused by changes in body representations. Instead of the rubber hand illusion, this experimental procedure implemented the mirror box illusion to cause the embodiment of an external object (Crivelli et al., 2021; Medina et al., 2015). Therefore, additional objectives of this study were the elicitation of the feeling of ownership towards the mirrored hand and the induction of the proprioceptive drift, as a byproduct of the mislocalization of the real hand towards the mirrored one.

The resulting hypotheses are the following:

1) In the synchronous condition, where both hands tap the screen at the same time, the mirror box illusion should induce the embodiment of the mirrored hand (i.e. the reflection of the hand outside the box). At the same time, the hidden real hand would be disembodied. Subjective reports in the embodiment questionnaire are expected to attest to this distortion of the body representations.

2) The embodiment of the mirrored hand should shift the perceived location of the hidden limb towards the mirror. In turn, this would lead to differences in the localization task conducted before and after the illusion, as a result of the proprioceptive drift. Pointings after the synchronous condition should be nearer the mirror than the ones done before the illusion.
3) After the mirror box illusion (i.e. synchronous condition), participants are expected to bisect with a bias towards the real hand, when carrying out the line bisection task. This would imply a reduction of pseudoneglect when the illusion is applied to the left hand. Such an effect is expected to be more significant for the left hand, as laterality plays a role in the effectiveness of the bias.
4) The vividness of the illusion should be proportional to the embodiment of the hand and, therefore, to the mislocalization of the real hand towards the mirrored one. Hence, a significant subjective feeling of ownership reported in the embodiment questionnaire should correspond to an equally significant proprioceptive drift in the localization task.

As expected by the hypothesis of this study, Mirror Box Illusion effectively elicited the embodiment of the mirrored hand in participants. Results gathered from the embodiment questionnaire and the localization task convey supporting evidence. Indeed, after synchronous stimulation in the MBI, participants reported an increased feeling of ownership towards the hand reflected in the mirror. The items in the questionnaire subtending the feeling of ownership towards the mirrored hand (i.e. "it felt as the hand in the mirror was my hand"; "it felt like the index finger of the hand inside the box was touching the index finger of the hand outside the box") systematically reported a higher score in the synchronous condition, compared to the asynchronous one. Other statements in the questionnaire showed a similar pattern, such as the feeling of agency ("it felt like I was in control of the hand in the mirror”) and the subjective proprioceptive drift (“it felt as my hand was in the same position of the reflected hand”). Overall, these findings advocate for the efficacy of the Mirror Box Illusion in inducing the subjective sense of embodiment towards the hand reflected in the mirror.

At the same time, the localization task highlighted the indirect effect of the MBI. Indeed, pointings after the illusion (i.e. synchronous condition) were closer to the edge of the box, towards the mirror. The MBI effectively induced a shift in the perceived location of the hidden hand. Therefore, participants felt as if their hidden hand was closer to the mirror, resulting in proprioceptive drift. Surprisingly though, proprioceptive drift was also present after the asynchronous condition, but only when the Mirror Box Illusion was applied to the left hand. Such findings could be explained by considering the modest weight of incoherent tactile and proprioceptive feedback with respect to visual information, in determining the somatoperception of the hand (Rohde et al., 2011). Further speculation on the topic will follow.

Along with the expectations of this study, the vividness of the illusion, attested by the embodiment questionnaire, was proportional to the entity of the proprioceptive drift. In other words, participants who reported a significant feeling of ownership in their subjective report, also presented a marked difference in the pointings between before and after the illusion.

Contrary to the hypothesis of this study, MBI resulted in a non-significant effect on the line bisection task. In fact, participants' performance in the bisection of the horizontal lines did not shift significantly after the induction of the illusion. At the same time, no difference emerged between the synchronous and asynchronous conditions. There was no sign of interaction linking the synchronous condition in the MBI to the line bisection task. Altogether, this evidence suggests that, in the present study, the Mirror Box Illusion has failed to modulate the spatial representation. This could be due to the difference in experimental design between Ocklenburg's procedure (Ocklenburg et al., 2012) and the one implemented in this study.

However, in the line bisection task, the physiological pseudoneglect (Jewell & McCourt, 2000) was detected only when participants bisected using their left hand. In other words, the leftward bias was absent when the bisection task was conducted with the right hand. This finding poses questions on the possibility of a laterality effect (Zago et al., 2017).

4.1: Mirror Box Illusion Induces Feeling of Ownership Towards the Mirrored Hand

The Embodiment Questionnaire (Crivelli et al., 2021; Medina et al., 2015) provided insight into the phenomenological aspects of the Mirror Box Illusion. By using a psychometric approach, participants' subjective reports allowed to investigate the first-person perspective of the illusion, as well as the resulting embodiment of the mirrored hand. As hypothesized by this study, the synchronous condition elicited the highest embodiment ratings. Indeed, items regarding the subjective feeling of ownership, the mislocalization of the biological hand, and the sense of agency all presented higher scores after the synchronous MBI. In this regard, the present study replicates the findings from Medina et al. (2015).

Additionally, as in Medina et al. (2015), the asynchronous condition resulted in a decreased sense of agency. The latter is often defined as the result of the congruence between predicted and observed sensory states (Farrer & Frith, 2002; Sato & Yasuda, 2005), so that if an action follows its prospected course in reality, the sense of agency over what has happened increases. In these regards, the asynchronous condition provides conflictual multi-sensory information. As a matter of fact, the tapping of the hand inside the box was felt at the least predictable moment, which is when the reflected hand was detached from the mirror. Conversely, whenever participants saw the reflected hand touch the mirror, they expected a corresponding haptic feedback. However, no tactile sensation could be provided by the hidden hand, because in those moments it was detached from the surface of the box. This mismatch between prediction and reality, vehiculated by conflicting multisensory information, is a plausible reason behind the decrease in the sense of agency after the asynchronous condition in the MBI.

For the same discrepancy in sensory feedback, the feeling of de-afference was expected to be more significant in the asynchronous condition, compared to the synchronous one. Surprisingly, the score across conditions was comparable. This could be due to the nature of the movement. In the MBI procedure, participants were instructed to carry out relatively precise movements for 60 seconds (i.e. tapping fingers on the mirrors). This choice differs in a meaningful way from other works employing the MBI, where more gross arm and hand movement were implemented in the asynchronous condition (Fink et al., 1999; Foell et al., 2013; McCabe et al., 2005). A possible explanation lies in the slight differences in tapping rates between the two hands, which created enough incongruence to cause modest deafferentation even in the synchronous condition.

4.2: Visual Information Overtakes Proprioceptive and Haptic Feedback in Proprioceptive Drift

The synchronous condition of the Mirror Box Illusion managed to elicit a significant proprioceptive drift in participants. Indeed, the stronger visuomotor congruence (i.e. synchronous tapping) resulted in an increased bias towards the seen position of the hand. This finding goes coherently with the study by Medina et al. (2015). A broad variety of studies agree on a possible explanation for proprioceptive drift; the visual capture of touch (Holmes et al., 2004; Medina et al., 2015; Ocklenburg et al., 2012; Rohde et al., 2011; Tajima et al., 2015). As described in Pavani et al. (2000), the visual location of the artificial hand (i.e. the mirrored hand) is not the true location of the participants' hand, for which proprioception and touch should provide feedback. However, proprioception has a lesser spatial acuity compared to vision (Rock & Victor, 1964; Wann & Ibrahim, 1992; Warren & Cleaves, 1971). Therefore, visual feedback has more weight in multisensory integration. Most of the time, sensory inputs from different modalities render a coherent representation, in which touch, proprioception, and vision provide unanimous information. In cases such as the MBI, when multisensory information is conflicting, visual feedback is dominant and captures tactile and proprioceptive feedback onto the seen position of the hand, ultimately leading to the proprioceptive drift. From a Bayesian perspective, visual information goes accordingly with other sensory inputs in the majority of the scenarios, so it is adaptive to interpret ambiguous situations entrusting the most acute sense. Only in cases where conflict between multisensory information is irreconcilable, such as postural misalignment (Farnè, 2000), the visual capture of touch fails.

As stated above, the perceived position of the hand was more significantly shifted by the visual capture in the synchronous condition. In other words, when participants tapped the mirrors at the same time, thus achieving a coherent visuo-tactile stimulation, multisensory congruence heightened the proprioceptive drift. This finding is consistent with the temporal rule of multisensory integration (Meredith et al., 1987), in which inputs from different modalities are more easily assimilated if they are temporally coincident.

On the contrary, in the asynchronous condition, conflicting sensory information is not limited to proprioception. The disharmonious tapping provides contradictory tactile feedback that is detrimental to the visual capture. Ultimately, this should lead to a decrease in the size of the proprioceptive drift, since the perceived location of the limb is conflicting with the seen position of the hand. This was the case when the localization task was carried out with the right hand (i.e. MBI applied to the left hand), after the asynchronous condition. Surprisingly, the same was not valid when the localization task was conducted with the left hand (i.e. MBI on the right hand). Indeed, a significant proprioceptive drift occurred despite conflicting multisensory information coming from the left hand inside the Mirror Box.

This is not the first instance of proprioceptive drift during MBI asynchronous condition (Medina et al., 2015; Rohde et al., 2011). Medina et al. (2015) reported that even in the asynchronous condition participants experienced their limb as closer to the mirror, compared to asynchronous tapping without viewing the reflection of the hand. Proprioceptive drift occurs despite the presence of strong multisensory evidence advocating that the visual information is not reliable. Evidence such as the temporal asynchrony experienced between visual estimates on the hand and the tactile and proprioceptive feedback coming from the other limb (i.e. the hand inside the box). A possible explanation for this bias lies in the overtaking weight of visual information during multisensory integration. Classic studies on visual capture (Welch & Warren, 1980) have consistently reported a strong influence of visual information over the proprioceptive estimate of the limb position, even in a static condition without movement of the hand. Moreover, seeing the reflection of a moving hand in the same position as a passive hidden hand increased motor-evoked potentials, lateralized readiness potentials, and somatosensory evoked potentials for the static hand (Funase et al., 2007; Garry et al., 2005; Touzalin-Chretien et al., 2010). In other words, just by seeing the reflection of a moving hand, physiological activation occurs in the brain regions responsible for the representation of the hand behind the mirror.

Additionally, not all sensory information is discrepant to visual feedback. Even in the asynchronous condition, there is cross-modal congruence between modalities, such as the size and orientation of the limb. Since an individual experiences seeing and feeling their limbs in the same location throughout his/her lifetime, having a realistically sized and oriented within peripersonal space could be enough to create a significant bias toward the visual estimate (Lloyd, 2007).

To close the circle, proprioceptive drift would arise only for the left hand for the same reason that explains pseudoneglect (Zago et al., 2017). Indeed, hemispheric asymmetries in the allocation of spatial attention could determine a laterality effect that renders the left hemifield more susceptible to the illusion.

Altogether, these findings advocate for the dominance of visual information over less precise sensory modalities such as proprioception and touch in determining a coherent representation of the body. Discrepant multisensory feedback is disambiguated by the weight of visual modality in somatoperception. A weight important enough to determine visual capture despite the presence of strong contradictory evidence, shifting the perceived location of the hand towards the visual estimate, ultimately leading to the proprioceptive drift.

4.3: Subjective Reports of Ownership and Proprioceptive Drift

A significant relationship was found between the ratings of ownership of the reflected limb and increased proprioceptive drift. Similar results were described in Medina et al. (2015), where participants reported two states. At first, a sense of seeing one hand in one position while feeling the same hand in another position. Subsequently, participants stated that their felt hand would bind onto the visual image, resulting in the disambiguation in the position of the limb and the feeling of a unitary hand. A plausible explanation is that the increased sense of ownership is a direct consequence of strong visual capture. Indeed, this binding across senses would be responsible for the stronger feeling of ownership towards the reunited limb. In these regards, the feeling of ownership would be the result of the effectiveness of the visual capture in disambiguating the locations of the hand.

4.4: Mirror Box Illusion Fails to Modulate Pseudoneglect

The only significant interaction resulting from the Line Bisection task was a more significant leftward bias when horizontal lines were bisected with the left hand. This finding is consistent with the physiological pseudoneglect that is present in the neurotypical population. Other studies report convergent evidence, advocating for a more significant leftward bias when the line bisection is carried out with the left hand (Jewell & McCourt, 2000; Ochando & Zago, 2018; Scarisbrick et al., 1987). The absence of a leftward bias for the right hand could be explained by the same nature of pseudoneglect, which is more pronounced for the left visual and motor hemifield. This is due to the hemispherical asymmetries in the spatial distribution of attentional resources (Zago et al., 2017).

Mirror Box Illusion did not elicit any significant effect, nor interaction in the line bisection task, thus confuting the hypothesis of this study. The embodiment of the mirrored hand and the consequent shift in the subjective body midline did not influence the representation of space. This evidence goes against the work from Ocklenburg et al. (2012), where the Rubber Hand Illusion modulates pseudoneglect in a line bisection task. In all likelihood, the missing reiteration of the findings from Ocklenburg et al. (2012) is imputable to the differences in the procedure of the studies. The implementation of the MBI over the RHI is not the only factor setting apart the two. Given the lack of experimental procedures similar to the one presented in this thesis, speculations on the reasons behind the missing replication need a disambiguation that only future studies will attain. In the meantime, a series of plausible explanations will be discussed, in order to orient the research on the topic that has to come.

The most significant differences between this work and the one by Ocklenburg et al. (2012) are two: the implementation of the MBI and the task used to attest the proprioceptive drift. The latter insists on a motor task, where the effector (i.e. the hand outside the box) executes a ballistic motion to indicate the perceived position of the hidden limb on the surface of the box. This wide action implies postural changes, such as joint angle modification, and muscle activation that could increase awareness of the hidden limb. In turn, this could nullify the shift in the subjective body midline caused by the MBI, ultimately reducing the modulation of the illusion on the subsequent line bisection task. Despite postural and proprioceptive feedback play a minor role in multisensory integration when compared to vision (Làdavas et al., 2000; Rock & Victor, 1964; Wann & Ibrahim, 1992; Warren & Cleaves, 1971), they still provide valuable information to the body representation. As previously discussed, the implausible posture of the rubber hand in relation can impede the embodiment of the artificial limb when it is compared to the participant's body (Farnè, 2000).

An effective countermeasure in this direction would be the adoption of localization tasks that do not insist on motor response. As a case in point both Crivelli et al. (2021) and Medina et al. (2015) opted for a verbal equivalent, where participants indicated the perceived position of the limb inside the box by saying where it was in relation to a ruler attached to the box.

Another possible criticality related to motion is the Mirror Box Illusion itself. Contrary to the MBI, the Rubber Hand Illusion involves a more static position of the hand under the illusion, which creates a strong illusion of ownership towards the artificial counterpart (Botvinick & Cohen, 1998). In the MBI, the tapping motion provides on one side visuo-tactile congruency, that should strengthen the feeling of ownership towards the mirrored limb. However, actions performed by the limb under the illusion could raise awareness over the biological limb (Feldman & Latash, 1982), thus weakening the feeling of ownership towards the reflected counterpart. Indeed, both proprioceptive (i.e. kinaesthetic) and tactile feedback provide more conflicting information in the MBI, compared to the RHI, where the hand under the illusion holds a passive position. This multisensory discrepancy could still elicit proprioceptive drift, due to the strength of the visual capture (Farnè, 2000; Pavani et al., 2000). Nevertheless, the intersensory conflict could weaken the illusion and hinder the modulation of space.

In addition, it is the same nature of the mirror that could posit a hindrance in the modulation of space. Indeed, the perception of depth in mirrors is altered when compared to reality, and in this case to a three-dimensional object such as the rubber hand (Ocklenburg et al., 2012). Higashiyama & Shimono (2012) investigated the depth perception of pictures reflected by a mirror. By seeing these images in the mirror, participants reported an increase in the perceived depth of the pictures. Critically, this plastic effect in picture perception transferred to the actual picture. The mirror influenced the perception of depth in real objects. This alteration could counterbalance the modulation by the MBI in the line bisection. A bias would occur in the direction of the mirror box, due to the shift in the subjective body midline in the direction of the mirrored hand. However, this bias would be reduced by the altered perception of depth in space and in three-dimensional objects, such as the lines in the line bisection task.

4.5: Limitations of this Study

The present study is flawed by many limitations. First of which is the lack of an adequate control condition. Being a within-subject design, all participants carried out all conditions of the experimental procedure. This way, each person acted as a control for itself. The criticality emerged when the asynchronous condition, which should have acted as a control for the absence of the illusion, elicited significant proprioceptive drift. As previously discussed, visual capture together with the laterality effect (Zago et al., 2017) could be the culprit of such phenomena. In the RHI, asynchronous condition eliciting proprioceptive drift was also reported by Rohde et al. (2011). Hence asynchronous stimulation seems unfit as a control condition, since it acts as a proper stimulation, instead of a baseline condition. A possible solution could be introducing an additional condition without any tapping. However, the influence of visual capture could still determine a significant modulation, as displayed in Rohde et al. (2011), where even without any brushing participants reported a feeling of ownership towards the rubber hand. Therefore, a plausible provision would be a tapping condition where participants are not allowed to look into the mirror. This could limit the influence of the visual capture.

Furthermore, a potential modulation of the MBI on the representation of space could have been flawed by the position of the sheets in the line bisection task. Due to the experimental setting, participants had to position themselves with their body midline aligned with the surface of the box. This meant that the line bisection task had to be administered on a sheet positioned on the side of the box, and therefore, on the side of the participants. Ochando & Zago (2018) advocate for a significant effect of the position of the sheet on the line bisection task performance. As illustrated in this study, line bisection positioned on the right of participants presented a rightward bias when bisected with the right hand. Conversely, when the sheets were positioned on the left and bisected with the left hand, a leftward bias emerged from the participants' performance.

Another possible issue is the modest dimension and the representativeness of the sample, which consisted of young participants [mean age (SD)=22.42 ±4.53 years], and the vast majority were females (26 females, 10 males). In addition, they all attended the University of Pavia and they were all right-handed. For this reason, it was not possible to adequately investigate a laterality effect, since no left-handed participant was recruited.

Finally, the tapping in the MBI only lasted for 60 seconds, since the experimental design was taken from Crivelli et al. (2021) and Medina et al. (2015). On the other hand, Ocklenburg et al. (2012) stroked the participants' hand for a significantly longer time (180 seconds). Although the timespan implemented in this study was long enough to elicit both the feeling of ownership towards the mirrored hand and the proprioceptive drift, it is possible that a longer stimulation would have led to different results.

4.6: Implications of this Study and Future Perspectives

Given the specificity of the topic investigated in this work, the paucity of articles on the modulation between body representation and spatial representation does not allow to pinpoint the determining factors implied in the modulation of space in the RHI (Ocklenburg et al., 2012) that were absent in the current study. Future advancement will revolve around the solution of this conundrum. Implementing alternative experimental designs or variations in some of the tasks will shed light on the link between the two representations. Possible modifications were discussed in the previous paragraphs. As a case in point, introducing a condition where the mirror is not visible during the tapping would act as a more neutral "stimulation", that could provide a baseline for further observations. By comparing this neutral condition to the synchronous one, a clearer comparison should be possible, without confounding factors such as the visual capture in the asynchronous condition. Furthermore, lengthening the timespan of the stimulation could elicit a stronger illusion, that could imply different results. Another possible change could involve the localization task, by swapping a motor task with declarative judgements implementing a ruler installed on the box. These are but a few of the possible adjustments that in future research could allow a clearer perspective on the link between body representation and spatial representation.

Investigation on this topic is functional not only to the understanding of the disorders of the body representation but also to the discovery and implementation of new therapeutic approaches for the disorders in spatial representation. An example could be the applications on somatoparaphrenia (SP), a syndrome resulting from a lesion in the right hemisphere that causes a delusion of dis-ownership of the contro-lesional paralyzed arm, along with anosognosia and personal neglect (Vallar & Ronchi, 2009). Salvato et al. (2016) illustrated in a case study how manipulations in the patient's spatial attention can lead to the alteration of limb dis-ownership. They showed that the somatoparaphrenic symptoms worsened when the patient was interviewed from the left side of the bed, compared to the right one. Additionally, a transient remission of the SP symptoms was possible after the partial restoration of the body ownership of the paralyzed limb, which was achieved via left caloric vestibular stimulation. Along the same line of research, mirrors were implemented by Jenkinson et al. (2013) in the treatment of SP symptoms. In this study, a SP patient denied limb ownership of the left hand when viewing it directly, but when the same hand was seen via the reflection of a mirror, the feeling of ownership towards the limb significantly increased. The extent of such increase depended on spatial attention; when it was drawn to the proximity of the mirror, the participant was able to correctly recognize the limb, while when the attention was attracted near the body (i.e. peripersonal space) the patient's performance dropped.

Another example of the application of the paradigm employed in this studio is Mirror Therapy. The rationale behind this therapeutic approach is very similar to the one implemented in the MBI: a mirror is placed in the patient's midsagittal plane, hence mirroring the movements of the non-paretic side as if it were the affected side. Mirror therapy has shown its efficacy in many instances, such as improving motor function after a stroke, reducing motor impairment, and enhancing activities of daily living (Thieme et al., 2018). Corresponding increases in neural activity were found in areas involved with the allocation of attention and cognitive control (dorsolateral prefrontal cortex, posterior cingulate cortex, S1 and S2, precuneus), as well as with the excitability of the ipsilateral primary motor cortex (M1) (Deconinck et al., 2015). Mirror therapy was implemented in the treatment of spatial representation disorders such as unilateral neglect, eliciting an increase in the patients' awareness of the neglected field (Ramachandran et al., 1999) and an improvement in the star cancellation test and the line bisection test over 6 months (Pandian et al., 2014).

To summarize, the Mirror Box Illusion is a promising tool in the research of the representation of body and space, displaying both insightful evidence on the modulation of body ownership and spatial perception, and encouraging therapeutic results in the treatment of spatial and body representation disorders. Further investigations employing the MBI are sure to contribute to the solution of the conundrum behind the body-space link.

5: CONCLUSION

Taking into consideration the pivotal role of body representations across various cognitive domains, the present study aimed to investigate the extent of their influence on spatial representation. An extensive corpus of works has focused on the relationship between the body and the space with which it can interact (i.e. peripersonal space) (Berti & Frassinetti, 2000; Cardinali et al., 2009; Gallagher, 2000; Yamamoto & Kitazawa, 2001). The evidence gathered so far advocates for the plasticity of this space, which insists on equally plastic body representations. In other words, body representation can change the processing of peripersonal space. However, neuroscientific and neuropsychological research on the influence of body representation on the representation of the whole space is still modest. A study by Ocklenburg et al. (2012) displayed a modulation in the line bisection task as a consequence of the embodiment of a rubber hand. This work aimed at increasing the knowledge on this topic, portraying a more complex and multi-faceted depiction of the body-space relationship. Specifically, the objective of this work was to investigate how a change in body representations can affect spatial representation. To this aim, a Mirror Box Illusion was implemented to induce in participants the embodiment of an external object (i.e. the reflection of their hand). This embodiment was expected to cause a shift in participants' subjective body midline (i.e. proprioceptive drift), as the external object is included in the body representation. Ultimately, repercussions of these shifts were supposed to show in a Line Bisection Task, where participants were expected to present a bias coherent with their proprioceptive drift.

The subjective report of the participants confirmed the efficacy of the Mirror Box Illusion in eliciting the embodiment of the mirrored hand. Indeed, participants reported an increased feeling of ownership, sense of agency, and mislocalization of the biological limb after the

MBI. These items were identified as subcomponents of embodiment by Longo et al. (2008) and the interaction between the score in these questions and the synchronous condition replicated the findings from Medina et al. (2015). Additional confirmation of MBI's efficacy resulted from the localization task, where participants displayed an increase in proprioceptive drift after the synchronous condition. The difference in pointings executed before and after the stimulation was significant, as the perceived location of the hidden hand shifted from its real position to its reflection in the mirror. This could be attributed to visual capture (Medina et al., 2015; Pavani et al., 2000), since visual information of the reflected hand overcomes the discrepant tactile and proprioceptive feedback of the hidden hand. Surprisingly, asynchronous stimulation elicited significant proprioceptive drift for the right hand. This finding suggests that visual capture can lead to such a drift even in the asynchronous condition, when sensory feedback is extremely incoherent. Notwithstanding the efficacy of the illusion, MBI failed to show a significant effect on the line bisection task. Therefore, this study did not find any supporting evidence for the hypothesis that changes in body representation lead to equivalent changes in space representation. As a matter of fact, participants did not display a significant difference in line bisections after the stimulation. This study did not replicate the findings from Ocklenburg et al. (2012). The reason for this lies in the difference between experimental procedures. Compared to the Rubber Hand Illusion, the Mirror Box Illusion insists on visuo-motor coupling, which could increase awareness of the hidden limb and hinder any effect on the line bisection task. Another important difference lies in the nature of the embodied object. Contrary to the three-dimensional rubber hand, the object of embodiment (i.e. the mirrored hand) and the mirror itself could alter depth perception and ultimately affect line bisection performance.

Among the limitations of this study, the lack of an adequate control condition is the most important. The experimental design considered the asynchronous condition as the baseline for further observations taken in the synchronous condition. However, this is not admissible considering the significant proprioceptive drift that followed the asynchronous tapping. The positioning of the line bisection sheets represented another issue, since any possible modulation coming from the MBI would have been indistinguishable from the inherent positioning bias (Ochando & Zago, 2018). Despite the shortcomings of this study, it is still crucial to improve the experimental design and continue the investigation on the topic with future studies. Through further understanding of Mirror Box Illusion, implementations of this paradigm could be broader, and Mirror Therapy could provide benefits not only to patients suffering from body representation disorders (Funase et al., 2007; Jenkinson et al., 2013), but also from spatial representation disorders (Deconinck et al., 2015; Pandian et al., 2014; Ramachandran et al., 1999).

In conclusion, the potential of the Mirror Box Illusion spreads from research to clinical applications. It provides multi-faceted evidence on the relation between body and spatial representation, as well as innovative treatment perspectives for both spatial and body representation disorders. Future studies employing the MBI will surely contribute to the understanding of the relationship between body and space.

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