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Department of Brain and Behavioral Sciences (DBBS)
MSc in Psychology, Neuroscience and Human Sciences

HOW DOES MUSICIANS' MOTOR EXPERIENCE INFLUENCE THE SENSE OF OWNERSHIP? A PRELIMINARY STUDY

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Academic year:
2023/2024

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I. Abstract

Bodily self-awareness is a multidimensional construct defined as conscious experiences bound to the self as a unitary entity. Bodily self-awareness, among other components, encompasses the fundamental sense of body ownership. However, the way in which the modality of body ownership can be coherent and maintained is not fully comprehended. It has been claimed that integrating proprioceptive interoceptive and exteroceptive signals might have a crucial role in the senses of body ownership. Lately in literature, there is an increased focus on the contribution of long-term motor training to build and maintain a sense of body ownership. Motor expertise is an ability that characterizes specific populations such as musicians. The importance of playing a musical instrument for the anatomical, cognitive, and behavioral levels is a well-studied topic. However, the comprehension of the way in which this modality interplays contributing and maintaining a coherent sense of bodily self-awareness is not fully understood. It has been postulated that the integration of proprioceptive, interoceptive, and exteroceptive signals can also occur during movements. For instance, studies on healthy subjects, especially musicians, have suggested that musicians are less susceptible to the rubber hand illusion paradigm. The current study aims to investigate differences in bodily self-awareness components between musicians and non-musicians by applying the mirror box illusion paradigm. Results suggested that musicians showed less proprioceptive drift in both conditions, compared to non-musicians. Moreover, results showed significant differences between the groups in two subcomponents of embodiment, the location, and the deafference. Musicians compared to non-musicians experienced less difficulty locating their left hand, and they experienced less feeling of numbness. These results underline the importance of motor expertise and the importance of experience in prolonged movements, in maintaining a coherent sense of body ownership and bodily self-awareness.

Keywords: mirror box illusion paradigm, multisensory integration, proprioceptive drift, motor expertise, bodily self-awareness

1. General Introduction

Individuals continuously receive different signals from the body, coming from both the inside and outside multisensory channels. To perceive our bodies and the world, in space and time, our brain receives many inputs from various modalities and integrates them efficiently and accurately into a coherent representation (Liu & Medina, 2017). Different body representations result from the interplay between different personal beliefs and knowledge about the body and multisensory inputs that arrive and integrate into different sensory systems. Importantly, the main perceptive channels include proprioceptive, interoceptive inputs, and exteroceptive inputs like visual or tactile signals(Salvato et al., 2020). Moreover, different sensory modalities convey different inputs, integrated by giving a coherent sense of self and developing bodily self-awareness. Bodily self-awareness is defined as a multidimensional construct defining conscious experiences as a unitary entity (Berlucchi & Aglioti, 2010; Blanke, 2012; Blanke et al., 2015). Furthermore, self-consciousness suggests that individuals experience a unique conscious self continuously linked to the body (Lenggenhager et al., 2009; Longo & Haggard, 2012). Importantly the hypothesis of the existence of a body-matrix integrates neural representations and supports that body-matrix integrates somatotopic and peripersonal sensory data allowing the adaptation to changes and maintaining homeostasis (Moseley et al., 2012). Additionally, recent research on bodily self-awareness has assumed that it consists of three distinct components: the experience of owning a body referring to body ownership, the experience of being a body with a given location within the environment referring to self-location, and the experience of being the actor of our actions referring to the sense of agency (Serino et al., 2013). Especially the sense of body ownership is grounded in the multisensory integration of information from the inside and outside of the body(Crivelli et al., 2023). A coherent sense of ownership relies on both top-down internal models of the body and a congruent multisensory integration of several bottom-up signals (Tsakiris, 2010). Body ownership has raised the interest of neuroscientific research, leading to the development of several body illusion paradigms to investigate the alteration of body ownership through experimental manipulation of it. The most used body illusion paradigm is the rubber hand illusion paradigm (Botvinick & Cohen, 1998) however, also the mirror box illusion paradigm is a newer technique and it provides useful insights encompassing the component of active movements (Crivelli et al., 2021; Medina et al., 2015). It is important to focus on the movement component considering that recent studies investigated that the human body receives sensory inputs also during the movements. That means that interoceptive, proprioceptive information and sensory signals are encompassed with additional signals resulting from the movements (Pyasik et al., 2019). Based on that evidence, the main interest was whether movements contribute to and can modulate the sense of body ownership (Pyasik et al., 2019). Concerning body ownership and movements, studies have been conducted using the rubber hand illusion paradigm in different conditions, including movements, such as passive, active, or static. These studies provide mixed results supporting either that movements increased the feeling of illusion(Dummer et al., 2009), decreased the feeling of illusion (Walsh et al., 2011), or there was no difference between static or active conditions (Kalckert & Ehrsson, 2014). Moreover, from the other side, studies started to investigate the role of the absence of movements in clinical populations like patients with hemiplegia or tetraplegia and explore the differences in that sample (Burin et al., 2015). Beyond those studies, populations such as dancers or musicians are a challenge for further investigation into the involvement of motor skills in body ownership. There is undoubtedly a major gap of insight in this scientific area which is a challenge for further investigation of how the movements can affect the modulation of body ownership. Focusing especially on musicians, literature and neuroimaging studies have demonstrated important functional and structural changes at the brain level in musicians compared to non-musicians, especially in brain regions and neural networks crucial for the construction of a coherent bodily self-awareness (Elbert et al., 1995; Meister et al., 2004; Stewart et al., 2003). A study by Pyasik and colleagues (2019) on pianists using rubber hand illusion showed that pianists were less susceptible to the multisensory illusion, supporting the evidence for the contribution of motor skills to bodily self-awareness (Pyasik et al., 2019). It is interesting to focus on musicians, especially pianists because of their motor expertise, they are capable of processing distal movements differently from the non-musicians. In line with this idea, the present study investigates the contribution of motor expertise in maintaining bodily ownership after experimental manipulation. Thus, the sample was musicians, and specifically pianists. For this study, the mirror box illusion paradigm was used following the adaptation of Crivelli and colleagues (Crivelli et al., 2021, 2023). The concepts of body representation, bodily self-awareness, and body ownership, as well as the present preliminary study and its results, are presented in detail below.

1. Body Representation

1.1. Definition of Body Representation

Body representations are fundamental for everyday life, and, interestingly, numerous studies since the beginning of the 20th century have started to investigate them more systematically. Body representation refers to perception, memory, and cognition about the body, and one of its properties is the ability to be updated continuously by sensory inputs (Wen et al., 2016). The first definition given by Head and Holmes in 1911, interprets body representation as a map of our body in the brain. What makes body representation more complicated is the variety of sensory systems that integrate sensory inputs, and they are related to our bodies (HEAD & HOLMES, 1911). For instance, through touch, vision, motor behavior, emotional effect, semantic understanding, etc. (De Vignemont, 2010). Moreover, there are different distinct body representations, several of them are responsible for the process of primary sensory inputs, others are responsible for the control of motor outputs,(Zeharia et al., 2012) while other supplementary representations are involved in higher cognitive orders linked to more complex behaviors (De Vignemont, 2011). Another powerful and one of the most used definitions to identify body representation is developed by Longo (Coello & Fischer, 2015; Fischer, n.d.). According to that definition, initially, it is important to consider that our body has a dual character. On the one side, the body is the origin of our first personal perspective and subjective experience, the place of our sensations as an infinite feature of one's perception. Concerning this point, it provides immediate knowledge about our body from the inside as an object of direct perception. On the other side, the body is a physical object like any other, affected by external stimuli in the same way that other objects are affected. From this perspective, individuals cognitively reflect on their own bodies from the outside. Together these dual features provide implicit and explicit knowledge about one's body contributing to the creation of body representations (Longo, 2015). In other words, body representations, integrate abstract knowledge about the body with cognition and beliefs (De Vignemont, 2010; Paillard, n.d.). In the literature, Bonnier first used the term "schema" to refer to the spatial organization of internal bodily sensations. After this initial step and despite the confusion around the function of body representation, it was clear that mentioning body representation is not a simple construct but rather complex and important for everyday life. The movements, sensations, and body posture are examples related to body representations and significantly contribute to a well-functioning body (De Vignemont, 2010). Moreover, body representations are not rigid, but they have a diversity of dynamics and plasticity, properties that can also be observed in case of distortions like when patients are not able to correctly indicate body parts or bodily sensations, known as autotopagnosia (De Vignemont, 2010). Another feature of body representations is that they can be split as long-term or short-term. Long-term refers to relatively stable properties of the body like the spatial organization of body parts while short-term representation refers to body properties at a specific time (De Vignemont, 2010).

1.1.1. Taxonomies of Body Representation

1.1.2. Dyadic Taxonomy

Gradually different models of body representation, known as neuropsychological taxonomies, have begun to develop (de Vignemont, 2010). The first taxonomy is based on the principle of double dissociation. Double dissociation is present when a group of patients (1) perform well in task A and worse in task B while patients in group (2) perform worse in task A and good in task B. This is a strong form of double dissociation. The weak form of double dissociation is similar to the strong form, with the difference that both groups perform worse than healthy participants. So, the taxonomy based on that concept is called dyadic taxonomy and consists of the body schema and the body image (Dijkerman & de Haan, 2007; Gallagher, 2005; Paillard, 1999). In this taxonomy, the body schema is a part of body representation carrying sensorimotor representations that guide the actions. Despite this, body image is used to describe representations as perceptual, conceptual, and emotional. Body image seems that it is not linked to actions. Furthermore, several dissociations have been proposed to establish the dyadic taxonomy, such as the double dissociation between the deafferentation associated with the disruption of the body schema. To be more precise, differentiation is a disorder characterized by a loss or lack of tactile and proprioceptive information (Gallagher, 2005). Another example of double dissociation is the numb sense, accompanied by a tactile deficit with the preservation of touch-guided movements. Numbsense can be seen as a distortion of the body image (Paillard, n.d.). Moreover, Dijkerman and de Haan 2007, demonstrate from their studies data that show the somatosensory network processing related to the dyadic taxonomy. The somatosensory network for guiding action includes the involvement of the Posterior Parietal Cortex (PPC), and the insula is involved in the perception and body sensation memories (Di Vita et al., 2016).

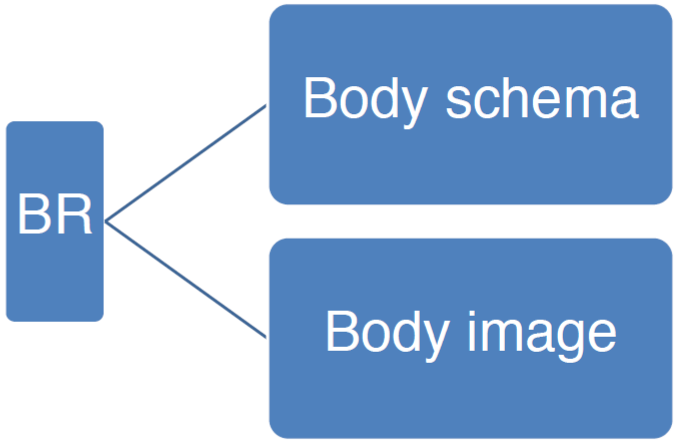

Figure 1. Dyadic Taxonomy.

1.1.3. Triadic Taxonomy

After the dyadic taxonomy, another, triadic taxonomy was developed. In the triadic taxonomy, the concept of body schema remains as it was in the dyadic taxonomy, however, the notion of body image is refused because of its heterogeneity. More specifically, the body image is divided into two distinct body representations, the body structural description or a visuo-spatial body map and the body semantics. The body structural description or visuo-spatial level, body image provides a structural description of the relationships between body parts. That means it gives information about their proximity or positions relative to each other. At the semantic level, body image is mainly conceptual and linguistic. Body semantics describes the functional purposes of body parts and the categorical relationship between them. For instance, the wrist and ankles are joints (De Vignemont, 2010) . As in dyadic taxonomy, there have been several dissociations also the triadic taxonomy is based on specific dissociations between apraxia, autotopagnosia, and body-specific aphasia. Starting with the first, apraxia is a clinical manifestation generally defined as a disorder of skilled movements that is not possibly to be explained by a peripheral deficit like movement weakness. Apraxia can be divided into two other categories ideational and ideomotor apraxia. The first results from the disturbance in the conceptual organization of actions while the second is a disorder of the production of sensorimotor programs, a disruption of the body schema. The second dissociation is autotopagnosia. Autotopagnosia is another clinical manifestation characterized by the mislocalisation of body parts and bodily sensations (De Vignemont, 2010). It is considered a disruption of the body's structural description. The third dissociation is body-specific aphasia, a disorder of body awareness with the main symptom, the loss of lexical knowledge about the body parts. This type of dissociation is related to the disruption in the body's semantics (De Vignemont, 2010; SIRIGU et al., 1991).

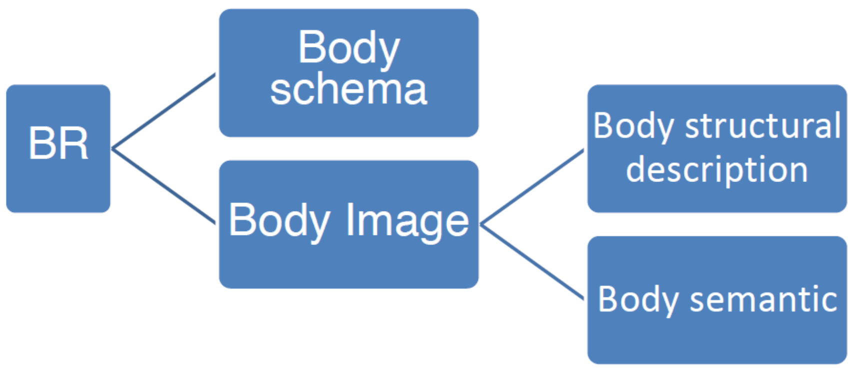

Figure 2.Triadic Taxonomy.

1.1.4. New Taxonomies

Later in literature six kinds of body representation were added and presented by Matthew R. Longo (2015). The general tendency of modern neuropsychology is to subdivide the previous initial schematic taxonomies into newer, more complex, and more modular models subdivided into other mechanisms. In literature, body schema is considered unconscious while body image is perceived as a conscious body representation (De Vignemont, 2010; Galfano & Longo, 2014; Longo & Haggard, 2010). More specifically, Longo 2015 presented a new taxonomy based on somatosensation a notion that refers to all the basic sensory mechanisms of the body like touch, and pain (Longo et al., 2010). In this new taxonomy, body representations are divided into the two general categories of somatoperception and somatopresentation. Somatoperception refers to the construction of higher percepts about the body or objects in the world. Somatopresentation refers to the basic knowledge about one's body and generally about bodies. So, these two categories of somatoperception and somatopresentation include the six body representations. In the category of somatoperception, there are body schema, body image, superficial schema, and body model. Body image refers to subjective experience of the physical structure of our body in terms of its size and shape while body model is like body image but with larger distortions. In literature regarding clinical populations, body image is considered an important aspect of psychiatric disorders like eating disorders or body dysmorphic disorders (Fischer, n.d.; Phillips et al., 2008). Body schema refers to unconscious dynamic knowledge about body posture. The body superficial schema includes representations that mediate the localization of tactile sensation onto the skin surface. Furthermore, in the category of somatopresentation, there is semantics about the body and the body structural description. Body structural description represents knowledge regarding the topological organization, where the parts of the body are located. Lastly, body semantics include the linguistic representation of the body (Longo, 2015).

1.1.5. Models to Describe the Interactions Between Body Schema and Body Image

Pitron & de Vignemont, 2017 argued that three models describe the interactions between body image and body schema. More specifically, the first model, known as the fusion model, has adopted a purely biological perspective supporting the idea of a single, long-term representation of the body and is considered multifunctional. The second model is the independence model which focuses on the functional elements of the body representation therefore it supports the existence of two functionally different long-term body representations constructed separately. One is action-oriented while the other is perception-oriented. Lastly, the third model is the co-construction model where the body schema and the body image are functionally distinct, but their construction is merely based on their interactions (Pitron & de Vignemont, 2017). This model attempted to merge the biological and functional aspects presented in the previous two models. Because of the co-construction model, another model is proposed in which the body schema is built first, based on multisensory signals and prior knowledge, and contains motor expertise. After it is built, it can work as one of the priors for constructing the body image. The body image is thus not a mere copy of the sensorimotor representation. In the process of its construction, it gains complexity but loses detail and accuracy. Furthermore, body schema and body image can be distorted differently (Pitron et al., 2018). A study showed, that when two rubber hands are stroked synchronously with the participants' own hand, they reported ownership of two rubber hands, subsequentially pointing movements were influenced by one rubber hand only (Newport et al., 2010).

1.1.6. Perception/Action Model- A Functional Distinction

The perception-action model is presented in de Vignemont 2010 and the work of di Vita and colleagues 2016(De Vignemont, 2010; Di Vita et al., 2016). This model is based on the evidence that all the taxonomies accept the role of action-oriented representation for the body schema. An fMRI meta-analysis conducted by di Vita and colleagues focused on the exploration of neural networks on the level of body representations, as well as on the demonstration of possible segregated neural networks between the action-oriented body representation linked to body schema and the non-action-oriented body representations, linked to body image. The general results of the meta-analysis showed bilateral activation from occipital lobes to frontal lobes (inferior occipital gyrus, inferior and middle temporal gyri, supramarginal gyri, fusiform gyrus, precuneus). In the level of neural activation for the action-oriented representation, they demonstrate some areas like bilateral activation of the fusiform gyrus, precuneus in the left hemisphere, angular gyrus in the right hemisphere, mainly the primary motor cortex and the extrastriate area. In the non-action-oriented body representation, neural activation in the somatosensory cortex and supramarginal gyrus. A common network for the two representations was found in the left hemisphere, with precuneus and medial prefrontal gyrus to be included. It can be observed that the results from this study support the idea of the two different types of body representations (action-oriented and non-action-oriented). Also, it illustrates the different neural networks supporting each representation and their interactions (Di Vita et al., 2016). The figure below shows the neural activation for the action-oriented and non-action-oriented representations.

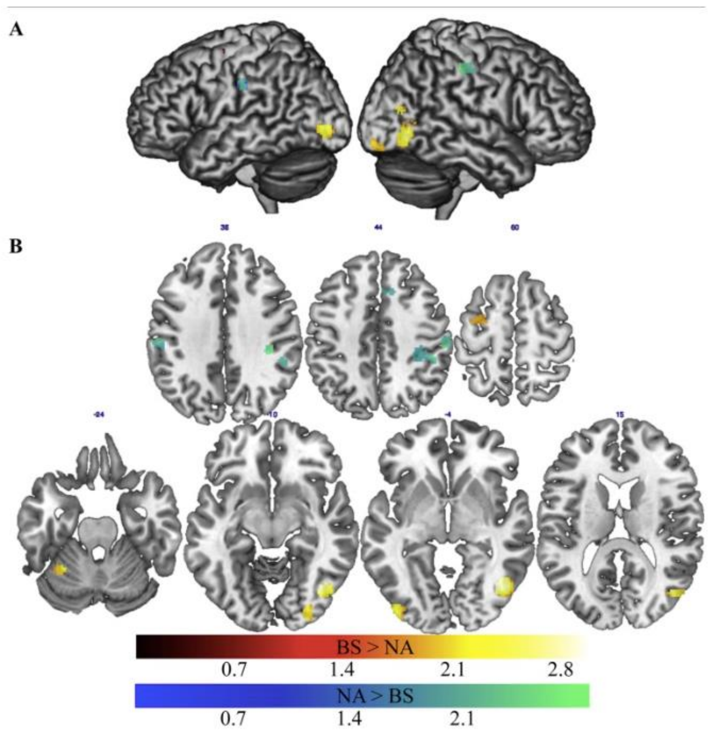

Figure 3. Red to yellow indicates activation for action-oriented (BS) while blue to green indicates the activation for non-action-oriented representations (NA)

1.2. Bodily Self Awareness

1.2.1. Definition of Bodily Self Awareness

Bodily-self-awareness is one of the conceptualizations for a coherent body representation. The concept of bodily self-awareness has influenced not only the field of neuroscience but has raised several doubts in philosophy. Bodily self-awareness, has been described as "the feeling that conscious experiences are bound to the self and are experiences of a unitary entity" (Berlucchi & Aglioti, 2010; Blanke, 2012; Blanke et al., 2015). Additionally, it refers to the relationship between the body and the self. (Vignemont, 2018). Bodily self-awareness is a multidimensional construct encompassing different bodily experiences. For instance, it involves aspects such as the experience of owning a body, the perception of visceral signals coming from one's own body, and feeling about one's own body in the space (Berlucchi & Aglioti, 2010; Blanke, 2012; Blanke et al., 2015). Bodily self-awareness is tough to arise from the integration of exteroception, proprioception, and interoception. By mentioning, exteroception refers to the integrated signal coming from the environment. The main function of exteroception is to receive signals like sounds, and lights from the environment and to make meaning to the external world after the processing of those signals (Quattrocki & Friston, 2014). Another dimension of bodily self-awareness is proprioception which integrates information about the position and movement of the body (Vignemont, 2018). The modality of proprioception includes muscle spindles, joint receptors, and Golgi tendon organs too (De Vignemont, 2014a; Longo & Haggard, 2010; Vignemont, 2018). In other words, proprioception processes proprioceptive and kinesthetic information allowing a coherent and adaptive execution of movements and giving a sense of agency (Quattrocki & Friston, 2014). Lastly, interoception provides us with information about the physiological states of the body to maintain its optimal homeostasis. Interoceptive signals come from several modalities like cardiovascular, respiratory, gastrointestinal, and urogenital systems (De Vignemont, 2014a; Vignemont, 2018). For instance, the immune system provides information about inflammatory changes. Interoception allows models of the internal "self" to be constructed and feelings to be inferred through visceral sensations such as temperature, stretch, and pain from the gut, light (sensual) nondiscriminatory touch, itch, etc. (see. Fig.5) (Boesch et al., 2016; Quattrocki & Friston, 2014). In the following sections, they will be provided with more detailed definitions concerning their role in bodily awareness.

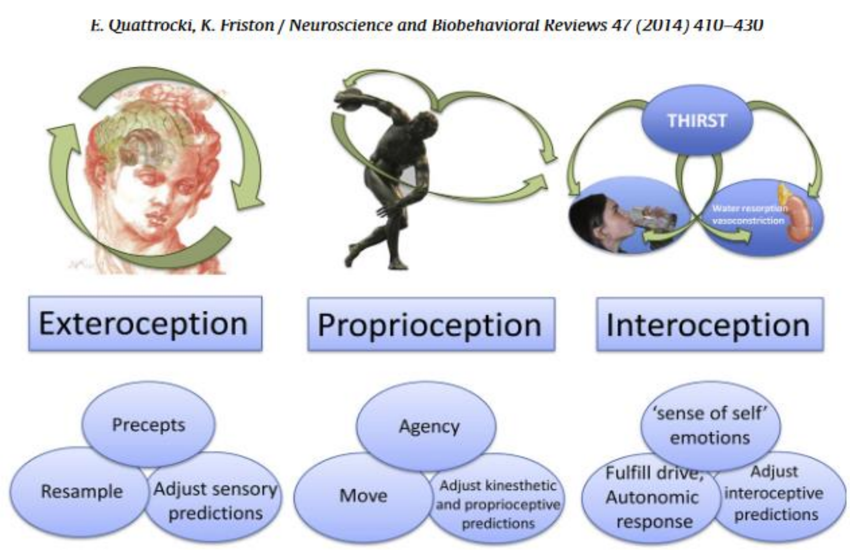

Figure 4. Description of Proprioception, Interoception, Exteroception

1.2.2. Proprioception

As mentioned above (see 1.2.1) proprioception is a dimension of bodily self-awareness and body ownership, which is known *as the awareness of the mechanical and spatial state of the body and its musculoskeletal parts* (Héroux et al., 2022). Proprioceptive signals are composed of peripheral inputs (from muscle spindles, Golgi tendon) with central inputs from efferent motor neurons. Finally, these signals lead to the perception of the position of the body, and the body movements which is referred to as kinesthesia (Héroux et al., 2022). Interestingly, proprioceptive signals are less intense when someone is not moving while they are more reliable about bodily posture when someone is doing a movement. Due to multisensory integration, proprioceptive and tactile signals can be affected by visual or auditory signals, and the external senses like vision can affect body senses like proprioception leading to an alteration of bodily experiences (De Vignemont, 2014b). Considering the Rubber Hand Illusion Paradigm (see later), visual information, looking at the rubber hand being touched, can alter proprioceptive and tactile signals about one's own limb (Botvinick & Cohen, 1998).

For the assessment of proprioception, it is critical to consider the complexity of this modality and to take into consideration the higher-level proprioceptive abilities. In high-level proprioceptive judgments, there are different frames of reference. For example, when someone is asked to indicate the location of the index finger according to a visible ruler when the upper arm is hidden, this is a high-level proprioceptive judgment that is relative to the external world and not concerning the body(different reference frame) (see. Fig. 6) (Héroux et al., 2022).

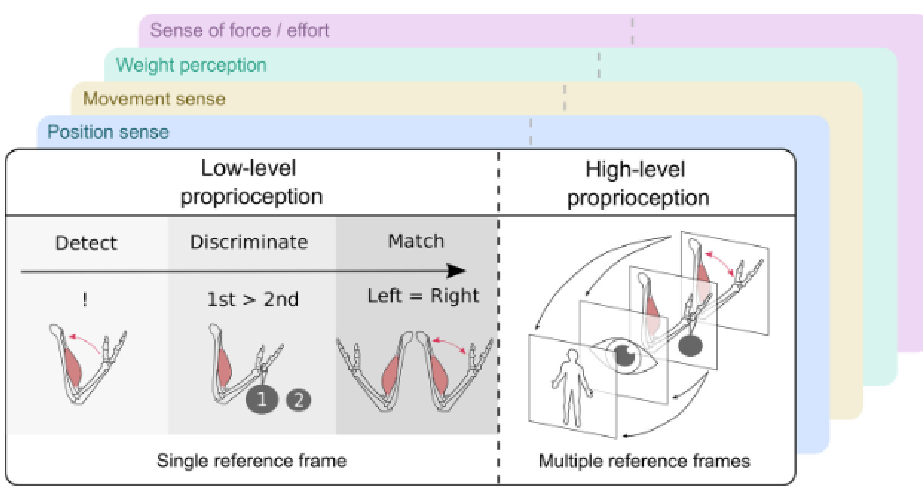

Figure 5. Schematic representation of human proprioception assessment.

The main measure used to quantify proprioception in the bodily illusion paradigm is proprioceptive drift which describes the shift in the perceived location of the limbs induced by an illusion of body ownership such as the rubber hand illusion or mirror box illusion (Rana et al., 2020). Finally, brain image studies in healthy participants and stroke patients showed great proprioception-related brain activation in high-level sensorimotor areas especially in the supramarginal gyrus (SMG) and dorsal premotor cortex (PMd) for the healthy participants. Additionally, it observed a dominance for the right hemisphere, especially in activation of the SMG. For the stroke patients, results showed less activation and laterality for the right SMG by indicating the importance of SMG and PMd for proprioception, in the spatial and motor processes while the reduced activation of SMG can be related to the decrease of proprioception (Ben-Shabat et al., 2015).

1.2.3. Interoception and Exteroception

Interoception and exteroception are the other two perceptive modalities that with proprioception shape and maintain bodily-self-awareness. Since interoceptive and exteroceptive signals play an important role in the sense of self, several researchers have focused their interest on a more detailed investigation of this interplay (Park & Blanke, 2019). From one side, exteroceptive information comes from the external world outside of the body, for example, auditory, visual, or tactile inputs, and based on how significant they are for the sense of body self-awareness, several experimental paradigms have been developed. For instance, in the rubber hand illusion paradigm (Botvinick & Cohen, 1998), and full body illusion paradigm (Salomon et al., 2013) when a mismatch in visuo-tactile information occurs, participants' sense of body ownership alters (Salvato et al., 2020).

On the other side, the interoception modulation integrates signals about the internal state of the body, and visceral responses (Berntson & Khalsa, 2021; Salvato et al., 2020). Interoception is supported by different complex neural circuits encompassing the interplay of afferent/ascending and efferent/descending neural pathways. More specifically according to Berntson and Khalsa 2021 mechanoreceptors, thermoreceptors, and chemoreceptors receive and integrate interoceptive signals from the periphery and the organs, and through afferent pathways these signals reach the central nervous system. A main afferent pathway, very pivotal to conveying interoceptive signals is the vague nerve (Berntson & Khalsa, 2021). Additionally, areas such as the nucleus tractus solitarius in the brainstem, the thalamus, the amygdala, the hypothalamus, the insula, the anterior cingulate cortex, the orbitofrontal cortex, and the medial prefrontal cortex are areas that receive interoceptive signals from the periphery. To better understand the interoceptive mechanisms is important to focus on the reciprocal interactions between the afferent and efferent neural pathways involved in interoceptive circuits. Efferent pathways include systems such as the endocrine system, autonomous nervous system, and immune system. These systems receive information about the internal state of the body and they regulate those internal states through autonomic efferent pathways (Berntson & Khalsa, 2021). This integration of the information through the interoceptive pathways has an evolutionary meaning and significantly contributes to perception, cognition, emotion, behavioral aspects, and the sense of self (Critchley & Harrison, 2013). Based on the knowledge about the role of interoceptive awareness in the sense of self, studies with the administration of rubber hand illusion paradigm with the measurement of interoceptive accuracy by heartbeat perception task showed that lower interoceptive accuracy associated with alterations in the sense of ownership (Tsakiris et al., 2011). In a meta-analysis conducted by Salvato and colleagues 2020, they investigated the integration of interoceptive and exteroceptive signals by analyzing brain imaging studies of the sense of ownership and how it can be modulated by exteroceptive signals and the role of interoception too. They found that those two mechanisms merge in the supramarginal gyrus bilaterally. Moreover, results showed a right-lateralized right network consisting of precentral, postcentral, and superior temporal gyri indicating that the integration of multisensory signals and the recalibrating of information from various incoming channels and spatial frames of reference are processes carried out by these higher-order brain areas (see fig.7) (Salvato et al., 2020).

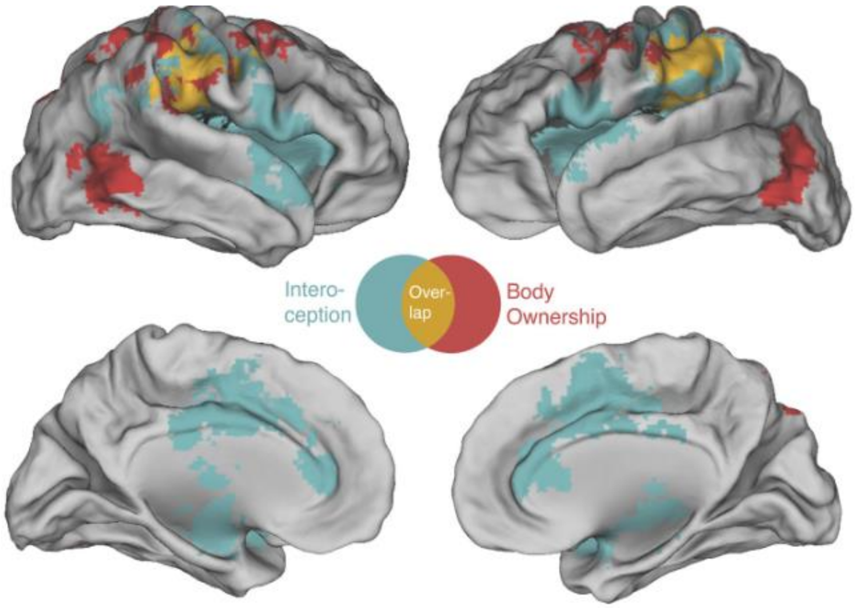

Figure 6.Overlapping activation of brain areas (yellow), related to interoception (light blue) and body ownership (red)

1.2.4. Neural Network of Bodily Self-Awareness

Bodily self-awareness is a multidimensional concept encompassing several aspects as they have been mentioned above. According to Morin (2006), bodily self-awareness is a superior form of self-consciousness referring to the capacity to focus on the internal environment, observing the process of self-information (Morin, 2006). Instead of focusing on the complex elements of this conceptualization, many researchers focused their interest on understanding how multisensory integration can be manipulated through illusion paradigms and thus modulate the experience of oneself (Serino et al., 2013). In literature, bodily self-awareness interplays with two other main components, distinct from each other which are, body ownership and self-location (Gallagher, 2000; Serino et al., 2013). Body ownership refers to the experience of owning a body. Body ownership will be mentioned in detail later. Self-location refers to the experience of being a body with a specific location within the environment (De Vignemont, 2011; Serino et al., 2013). According to the literature body ownership and self-location have distinct neural networks, although they interplay for some modalities. For example, in the study of Petkova and colleagues (2011), they observed neural activity in the ventral premotor cortex for the illusion of body ownership(Petkova et al., 2011). An unimodal sensory system is related to multisensory integration and might support body ownership and self-location. According to this model, each sensory input proceeded to a specific area. For instance, touch applied to a body part activates a specific area of the primary somatosensory cortex, also in the case of vision of different body parts activates specific portions of the extrastriate body area and occipito-temporal cortex (Serino et al., 2013). The unimodal system may not be sufficient to explain the experience of the body. Taking the example of lesions, according to this model, a lesion is caused by a specific deficit in the sensory system, however, this deficit does not induce any disturbance in bodily experience in general. Apart from this quite controversial statement, the unimodal system of body-related input is thought to be an input for multisensory integration taking place in the posterior parietal cortex and the ventral primary motor cortex (Blanke, 2012; Serino et al., 2013; Serino & Haggard, 2010).

The Posterior parietal cortex (PPc) is responsible for the transformation of several signals such as tactile, visual, proprioceptive signals, and vestibular signals related to specific body parts into stable spatial representations (Berlucchi & Aglioti, 2010). PPc has fundamental functions in the collection and encoding of multisensory spatial representations, in a way that ensures a coherent experience of self within the body. Giving some examples of left or right lesions in the PPc, like the patient's inability to describe spatial relationships between body parts of their own body or another's body (autotopagnosia) as well as the inability to recognize the contralesional body parts (personal neglect)(Committeri et al., 2007; Serino et al., 2013).

The ventral premotor cortex (vPMc) is related to the body ownership process. Authors supported that vPMc activated when subjects received tactile stimulation in a body part or when observed others being touched (Cardini et al., n.d.) The activation of vPMc is higher when a body or body parts that receive the stimulus do not belong to that subject (Serino et al., 2013). Results from studies using the rubber hand illusion paradigm showed increased activity in the vPMc in the synchronous condition (Cardini et al., n.d.). Lesions in this area induce disorders of bodily self-awareness like anosognosia for hemiplegia, a clinical manifestation referring to the lack of awareness of motor deficits in the contralesional bodyside (Berti et al., 2005). Moreover, according to a meta-analysis conducted by Salvato and colleagues (2020), body ownership is supported by the activation of several areas and more specifically, the inferior temporal gyri, the inferior occipital lobes, the postcentral gyri in supramarginal gyri, and the right parietal inferior lobe (Salvato et al., 2020). Also, generally, the multisensory integration is supported by the insular and posterior parietal cortex (Park & Blanke, 2019). A crucial area for multisensory integration is the temporoparietal junction (TPJ), responsible for the integration of different sensory stimuli and most importantly vestibular stimuli (Lopez et al., 2008).

1.2.5. Disorders of Bodily Self-Awareness

Bodily awareness is considered quite a complex and multidimensional notion. Bodily disorders can be observed in various contexts, in neurological conditions caused by peripheral lesions, or brain injury, and in a psychiatric context (De Vignemont, 2010). Given the variety of ways in our bodies to enhance the multisensory integration process like touch, vision, proprioception, etc., and the variety of bodily awareness disorders, they can explain why confusion around the body representation classification is there. To better understand the clinical conditions of body awareness disorders, it is important to consider the patient's subjective experiences and acknowledgments regarding the disorder (De Vignemont, 2010). For example, some patients have abnormal beliefs that are not founded on abnormal experiences like they mistake their index finger with their thumb. In other cases, patients have abnormal beliefs and abnormal experiences like in the case of somatoparaphrenia. The neuropsychological principle of double dissociation can contribute to classifying bodily disorders (De Vignemont, 2010). In this study, one of the bodily awareness disorders will be explained as an example: somatoparaphrenia.

1.2.6. Somatoparaphrenia

Somatoparaphrenia is a not common productive symptom of perturbation of body ownership. It is associated with right hemisphere lesions and profound motor and somatosensory deficits (Romano & Maravita, 2019) with the main characteristic that patients recognize that a limb is attached to their body however they explicitly support that the limb part belongs to someone else. More specifically it is a delusional belief that someone does not accept that the contralesional paralyzed limb belongs to his own body but that it belongs to someone else (Bottini et al., 2009; Salvato et al., 2016; Vallar & Ronchi, 2009). This manifestation has been associated with unilateral spatial neglect or anosognosia for hemiplegia. Evidence from several studies on somatoparaphrenia showed that deficits on the right fronto-temporo-parietal junction are crucial for developing this disorder. Also, in general lesions in the right parietal lobe and lesions in white matter and subcortical structures such as the thalamus, basal ganglia, and amygdala are involved in that clinical statement (Bottini et al., 2009; Gandola et al., 2012). Interestingly, in literature, the mechanism of caloric vestibular stimulation (CVS) can modulate behavioral and physiological aspects of body representation(Salvato et al., 2018). Based on that mechanism, Salvato and colleagues (2018) presented a case study of somatoparaphrenia and investigated changes in the body temperature before and after the CVS. The results show an increase in body temperature after the CVS accompanied by a temporary, short-term restored sense of ownership towards the paralyzed limb. These results, underline the importance of internal signals in the contribution of the coherence of body representation (Salvato et al., 2018).

1.2.7. Body Matrix

All the previous concepts of body representation and bodily self-awareness are integrated into the body matrix. Body matrix combines a dynamic neural representation including multisensory signals but also provides a body-centered spatial representation (Moseley et al., 2012). Concepts that have been analyzed above, interoception, and other components of the body self-awareness can be comprehended as their contribution to the sense of body awareness if they are examined into the coherent and dynamic framework of the body matrix. Body matrix is used to explain the multisensory representation of the space directly around the body, known as peripersonal space. The body matrix consists of neural structures and contributes to maintaining homeostasis at a physiological level and adapting to changes in the body structure and spatial orientation(Moseley et al., 2012). According to this condition, multisensory representations receive information from different brain areas, responsible for integrating different sensations, such as touch, vision, and proprioception. It is meaningful to note that body matrix representation is based on a body-centered frame reference and not on a hand-centered frame of reference evidence which is also the main difference between body matrix representation and other body representations. For body matrix representations, the position of the hands in the peripersonal space does not matter, also the presence of the stimuli in the peripersonal space is perceived as left or right depending on their side of appearance. However, abnormal feedback from other brain regions may modify this body-centered picture or may cause lower neural activation related to this representation. For example, a deficit in a part of this representation responsible for one side of the peripersonal space can be due to the alteration of the inputs received from the peripersonal part in charge of that information. According to this statement, unilateral spatial neglect can be either because of direct damage or failure to receive input from higher-level body representations (see. Fig. 8) (Moseley et al., 2012).

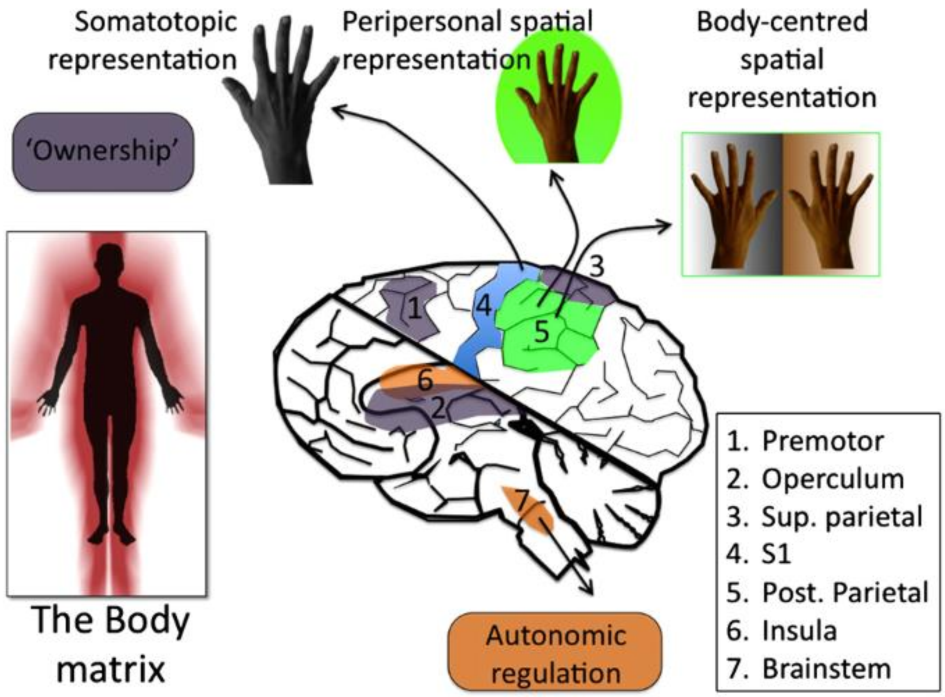

Figure 7. Body Matrix

Moseley and colleagues 2012 propose that the body matrix suggests an interplay between cognitive representations of body parts and physiological factors such as thermoregulation. Body matrix is based on the idea that several cortical regions, the most important being the posterior parietal cortex for spatial orientation and the insular cortex related to interoception, ownership, and homeostasis contribute to understanding the body and its functions. Multiple cortical representations provide multiple body representations in the brain (Berlucchi & Aglioti, 2010). Lastly, Moseley and colleagues 2012 support the idea that the body matrix would facilitate the integration of cognitive and physiological aspects of bodily experience, contributing to our sense of self and our ability to navigate and interact with the environment (Moseley et al., 2012).

1.2.8. Body Ownership

Sense of body ownership is a crucial aspect of bodily-self-awareness (Crivelli, 2021). In literature, there are several mentions of the sense of body ownership not only in neuroscientific literature but in philosophy as well. The empirical research on the field of the bodily self has recently started to explore the relationship between a body and the experience of that body as "mine". However, to grasp this manifestation, it is necessary to explain what it means by referring to body ownership since it is a multifactorial concept around which different models have been developed to explain it and various techniques to measure it. According to the definition of (Gallagher, 2000) from Tsakiris 2010, “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”. De Vignemont 2011 presented a distinction between the feeling of ownership and judgment of ownership. Concerning the feeling of ownership, many controversial opinions were raised. The main point is that someone is aware of his own body because of their knowledge. However, there is also the opinion that there is knowledge about our body however we also can feel it (De Vignemont, 2011). In de Vignemont 2011, body ownership is presented as the awareness of someone’s body belonging to someone’s self and the feeling that a given body part belongs to someone’s own body. In this definition of body ownership, the aspects of judgment and feeling of ownership are incorporated. Another definition was developed according to which a coherent sense of ownership relies on top-down internal models of the body and a congruent multisensory integration of external-bottom-up signals (Tsakiris, 2010). In (Longo & Haggard, 2012) body ownership is the feeling that my body is “mine”. In another study, body ownership is described as a perceptual experience of a body part as one’s own (Ehrsson, 2020). Several studies have attempted to measure the sense of body ownership in healthy participants by using different behavioral paradigms (Crivelli et al., 2021). Some of the methods that are mostly implemented are the Rubber Hand Illusion Paradigm (RHI) (Botvinick & Cohen, 1998), the Mirror Box Illusion Paradigm (MBI)(Medina et al., 2015), and techniques of full-body illusion (FBI)(Salomon et al., 2013). Often in literature, there is a connection between embodiment and a sense of body ownership. Embodiment refers to the subjective experience of having one’s own body(Medina et al., 2015). Moreover, embodiment is a factor that might affect the process of multisensory integration(Medina et al., 2015). Longo and colleagues attempted to identify embodiment and its subcomponents by using the rubber hand illusion paradigm (Longo et al., 2008a). In that study, the embodiment component dissociated into three main components: ownership, location, and agency(Longo et al., 2008a). The sense of agency refers to the fact that someone is aware of his actions and can control them (Haggard & Chambon, 2012). Sense of agency is similar to the feeling of ownership since the body boosts our actions (Caspar et al., 2015). Concerning the experimental research on the body-ownership, a relationship between temperature and sense of ownership it was observed. More specifically, the sense of disownerhip of a body part is related to some physiological changes like the reduction of motor potential or alterations in the skin temperature in healthy participants (Crivelli et al., 2021; della Gatta et al., 2016; Salomon et al., 2013). Nevertheless, those alterations in the temperature are obvious not only in the healthy population but also in the patients. For example, studies on brain-damage patients proved that specific thermoregulatory responses occurred in response to modulations on the sense of body ownership (Salvato et al., 2018; Van Stralen et al., 2013).

1.2.9. Neurocognitive Model of Body-Ownership

Body ownership is a complex and rich concept that triggers researchers to explore further and especially to investigate how the link between the body and the experience of the body as "mine" can be altered, developed, and maintained(Tsakiris, 2010). Based on this evidence, Tsakiris and colleagues (2010) have developed this neurocognitive model. In this neurocognitive model, body ownership arises as an interaction between current multisensory inputs and the internal models of the body. Initially, there is a pre-existing model of the body that can separate the objects that might or might not be part of that specific body. The pre-existing model of the body is a reference of the body properties, like visual, anatomical, and structural properties contributing to the recognition, identification, and distinction of our body. As a second level of processing, anatomical and postural representations of the body coordinate the integration of multisensory information in the corresponding systems. For instance, visual and tactile information that are coming from the external world, are considered multisensory inputs. The third level of that model is the outcome of multisensory integration which gives rise to the subjective experience of body ownership. This neurocognitive model involves a neural network comprised of the right temporoparietal junction (rTPJ) which tests the agreement of the external object, the secondary somatosensory cortex which maintains a line online representation of the body, the posterior parietal and ventral premotor cortex, and the right posterior insula which underpins the subjective experience of body-ownership(Tsakiris et al., 2007). An implication of this model is with the Rubber Hand Illusion (RHI) (Tsakiris et al., 2008). For the RHI the application of this model is as follows. In the first level, there is a comparison between the pre-existing top-down internal models and the current visual form of the object presented. The second level includes a comparison between the current state of the body and anatomical and postural bodily representations that are experienced as mine.

In the third level, it is compared the current sensory input with the felt touch. (Tsakiris et al., 2008).

1.2.10. Illusion Paradigm Tasks

Illusions that originate a sense of body ownership over a virtual body or a body part, are widely used to explore the complex relationships between the body representation that the brain creates and the body itself (Ehrsson, 2007). The following chapter relates to three main illusion paradigms, mostly used in literature. The first one is the Rubber Hand Illusion (RHI)(Botvinick & Cohen, 1998), the second one is the Mirror Box Illusion (MBI)(Medina et al., 2015) and the third one is the Full Body Illusion (FBI)(Ehrsson, 2007).

1.2.11. Rubber Hand Illusion (RHI)

Starting from the first one, the rubber hand illusion was originally studied by Botvinick and Cohen in 1998 when they used this experimental paradigm to test body ownership and bodily self-identification. (Botvinick & Cohen, 1998). The rubber hand illusion combines an interaction among visual, tactile, and proprioceptive inputs (Moseley et al., 2008). RHI offers a useful experimental manipulation of body ownership (Tsakiris et al., 2007). In the original study by Botvinick and Cohen, each subject was sitting with the left arm resting on a table. The left arm was hidden from the participant's view and in front of the participant was placed a rubber model very similar to the human size arm. Participants received the instructions to look at the artificial rubber hand while the experimenter was stroking with two paintbrushes the real hidden hand and the rubber hand as synchronously as possible(Botvinick & Cohen, 1998). After ten minutes, participants completed questionnaires relevant to their experience. Results showed that they experienced the illusion of a rubber hand meaning that they felt the touch of the rubber hand as it was in their own hidden left hand. Also, they showed some distortions concerning the position of the left hand, they perceived it as closer to the rubber hand. In a second experiment, they replicated the previous experience, but in a prolonged version. In this prolonged version, they tested the proprioceptive inputs and whether there were distortions. Results showed that with longer periods of illusion, participants had higher proprioceptive distortions when asked to judge the alignment of the right index finger to the left index finger with closed eyes. They placed their right finger closer to the rubber hand than their real left hand(Botvinick & Cohen, 1998). This change in the perceived location of the hand after the illusion is called proprioceptive drift (Rana et al., 2020). Similarly in Moseley and colleagues in 2008 RHI, typically is raised by stroking a person's hand which is hidden while synchronously stroking the rubber hand. In this task, many people perceive the stroke of the rubber hand as if it is on their own hand(Moseley et al., 2008). According to brain imaging studies, when a participant shows ownership towards the rubber hand, that induces cortical responses in parietal, premotor, and insula areas(Lloyd et al., 2006; Tsakiris et al., 2007). Figure 9 below represents the process of RHI induction (Moseley et al., 2012).

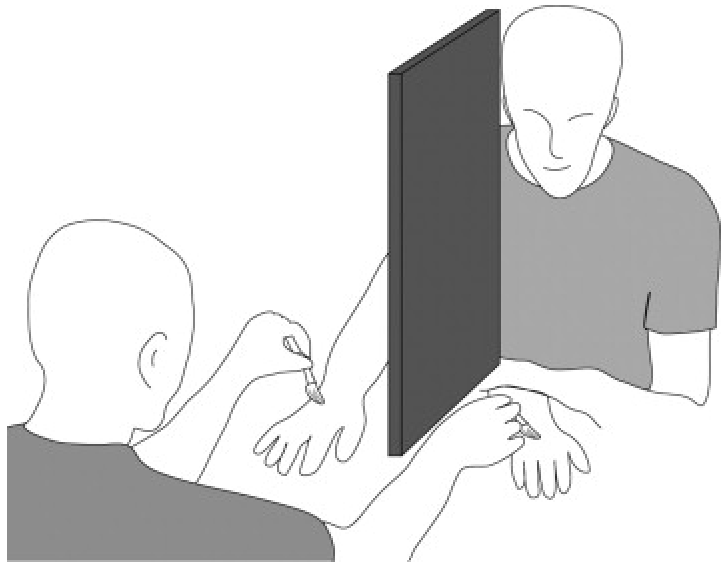

Figure 8. Experimental setup and induce of the RHI.

This illusion does not occur when the rubber hand is stroked asynchronously concerning the participant's own hand. For this reason, RHI allows an external object to be treated as part of the body, or not, under experimental control (Tsakiris et al., 2007). In this illusion paradigm Tsakiris and colleagues 2006, distinguish the integration of the visual and tactile inputs as *causes* of the RHI, referring to the multisensory stimulation and the *effect* of RHI as the feeling of ownership. More specifically in their study participants were watching their left or right rubber hand being touched synchronously or asynchronously in response to their hidden right hand. Moreover, a PET scan was used to demonstrate the brain areas were involved with the sense of ownership. The results (Figure 10) illustrated that body ownership was related to the activity of the right posterior insula and right frontal operculum while when the RHI was not induced to the real hand, in the asynchronous condition, an activation of the somatosensory cortex was observed (Tsakiris et al., 2007). Moreover, brain-imaging studies associated the RHI mainly with the activation of the multisensory premotor cortex, posterior parietal areas, and right posterior insula(Ehrsson et al., 2004).

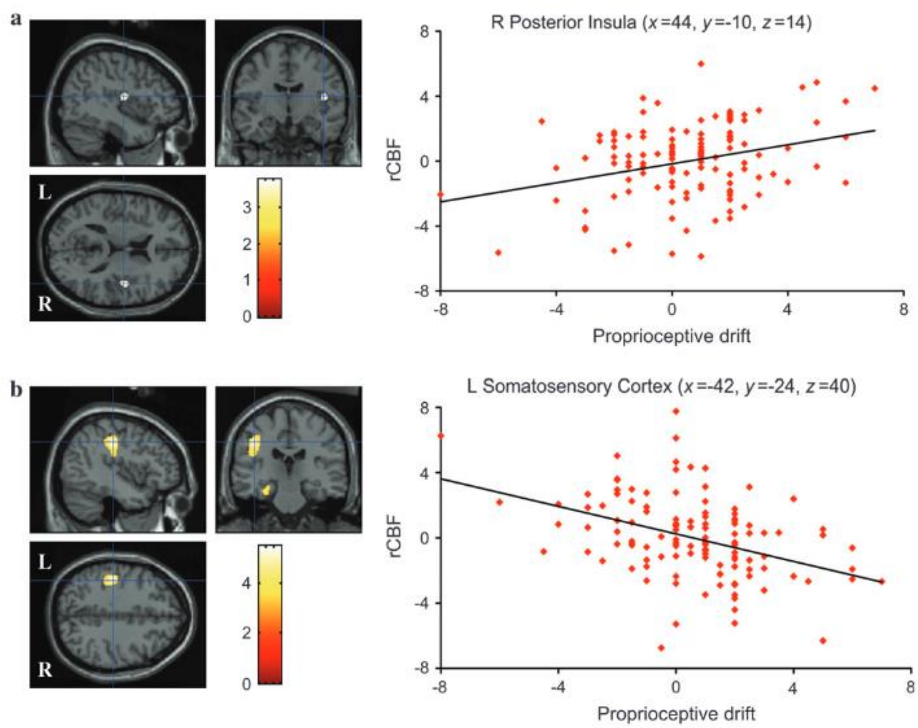

Figure 9.Activity in the right posterior insula positively correlated with proprioceptive drift. b. Activation of the somatosensory cortex has a negative correlation with proprioceptive drift.

Finally, the review conducted by Makin and colleagues (2008) gathered different theoretical aspects and observations around the implementation of the RHI, the alterations in proprioception, and the activation of brain areas involved. The authors proposed a model of the rubber hand illusion including multi-sensory peripersonal mechanisms. This model represents the transformation of the visual (red), somatosensory (blue), and multisensory (purple) information in the premotor cortex to contribute to the multisensory peripersonal processing during the RHI. Figure 11 represents this model (Makin et al., 2008).

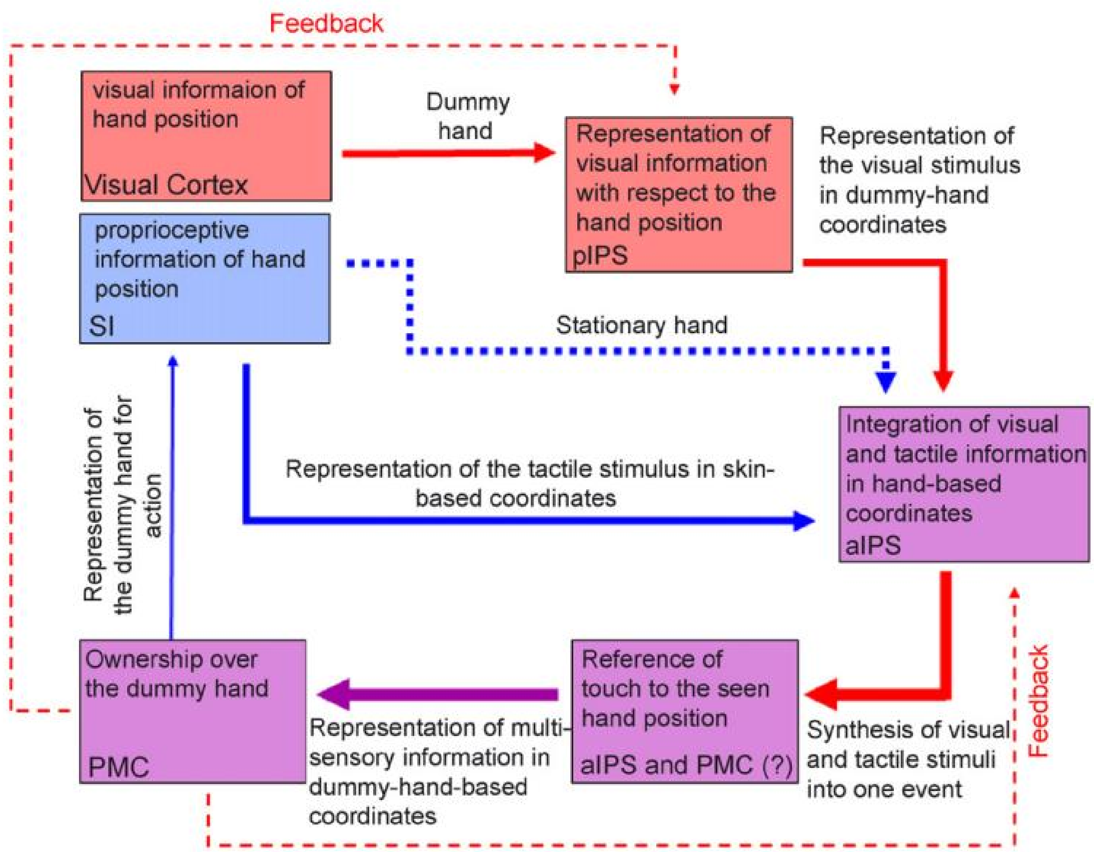

Figure 10. Peri-hand mechanisms involved in Rubber Hand Illusion.

1.2.12. Mirror Box Illusion Paradigm (MBI)

MBI constitutes another experimental paradigm for the study of body ownership. In literature, the work of Medina and colleagues 2015, was fundamental for introducing the MBI in experimental studies for healthy and non-healthy populations (Medina et al., 2015). The MBI is based on the concept of multisensory integration, the fact that sensory information from different sensory systems is integrated into a coherent representation and leads to the estimation of limb position. For example, in the case of the MBI, vision with proprioception contributes to estimating the limb position (Liu & Medina, 2017). This specific illusion paradigm overcomes the limitations of the rubber hand illusion. Initially, in the case of MBI, the illusion is actively induced by the subjects themselves, controlling the possibility of the influence of the experimenter on the experience of touch. Moreover, in contrast to the RHI, in which the visuo-tactile procedure is unilaterally applied, in this case, both hands actively touch the mirrors' surfaces in both conditions (Crivelli et al., 2021). Lastly, the MBI involves not only the synchronization of the tapping but importantly involves and requires bimanual coordination.

MBI has specific processes, and individuals place a hand on each side of the mirror. When the participant looks at the mirror, the reflection of the hand in front of the mirror is like the reflection of the hidden hand (see. Fig. 12). This conflict between the visual input and the proprioceptive input is important for the experimental manipulation of bodily self-awareness. In the study of Medina and colleagues 2015, they aimed to examine the relationship between the embodiment components (such as deafference, ownership, and location) and multisensory integration, when multisensory integration was manipulated. Deafference is a component used to describe the feeling of numbness, less vivid for the real hand(Longo et al., 2008a; Medina et al., 2015). In this study, participants were asked to tap both hands synchronously, asynchronously, or to make no movements in the MBI. Participants' right hand was hidden, and they were asked to focus on the reflection of their left hand in the mirror while tapping. In the non-movement condition, participants were asked to look at a black surface in the place of the mirror. Results showed that participants displaced their right hand mostly in the synchronous condition, less in the no movement condition, and the least in the asynchronous condition. Results also showed a positive correlation between the illusory visual displacement of the right hand and the sense of deafference for the asynchronous and no-movement conditions. Also, in the case of the synchronous condition and no movement condition, they found a positive correlation between the visual position and the sense of ownership towards the reflected limb. Previous studies showed similar results with Medina demonstrating that spatial manipulation can affect the tapping to reach some endpoints (Holmes et al., 2006). Using the MBI, more recent studies have been conducted (Crivelli et al., 2021, 2023). The first one, from Crivelli and colleagues, aimed to investigate the relationship between an implicit measurement such as skin temperature and the sense of body ownership. Results showed that alterations in the sense of body ownership can be linked to changes in skin temperature and thermal sensitivity (Crivelli et al., 2021). The next study by Crivelli and colleagues 2023 was based on the asymmetry of the sense of ownership with the right hand as the dominant. Indeed, results showed that the alteration of body ownership was greater in the left hand and therefore the temperature alterations were greater in the left hand too (Crivelli et al., 2023).

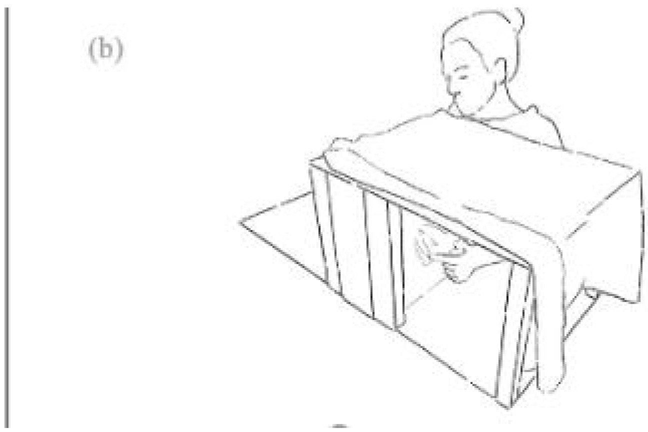

Figure 11. Mirror Box Illusion

1.2.13. Full Body Illusion Paradigm (FBI)

Full-body illusion has been used in the neuroscience research field as a method to induce a sense of disownership (Crivelli et al., 2021). FBI can be applied to healthy participants and a clinical sample like patients with out-of-body experiences (Lenggenhager et al., 2007). The FBI is similar to the rubber hand illusion paradigm, but the difference is that participants are not exposed to a rubber hand but to a virtual body. At the FBI, subjects wear a head-mounted display (HMD) that displays a video picture connected to a video camera. The video camera is positioned two meters behind the subject and records the subject's back. As a result, participants watched a video representation of their own body as a researcher gave them a stick stroke which they felt on their own back and in the virtual body's back. HMD generated synchronous and asynchronous visuo-tactile stimulation by displaying the stroking of the virtual body either in real time or not by using an online video delay or offline pre-recorded data (Lenggenhager et al., 2007; Salomon et al., 2013). FBI and RHI are mainly measured following some questionnaires and behavioral tasks. Lenggenhagen and colleagues 2007 pointed out that RHI studies have investigated alterations in body ownership for body parts, while the full-body illusion paradigms aim to investigate whole body representations, entire body ownership, and notions related to the sense of selfhood. Their study aimed to induce out-of-body experience in healthy participants. They used virtual reality (FBI) following the process described above regarding the application of the FBI. Participant's backs were stroked for 1 minute synchronously or asynchronously concerning the virtually seen body. Results showed that participants experienced a shift of their self-position toward the virtual image for the synchronous condition and on the anterior-posterior axis (Fig. 9). In a follow-up investigation, they investigated whether the drift towards the virtual body was not due to a general motor bias to overreach the target position and whether this illusion is dependent on cognitive understanding about bodies. They either displayed the participant's actual body, a fake body, or an object by being stroked synchronously or not using a constant time delay in asynchronous conditions (Lenggenhager et al., 2007). Results showed that participants had out-of-body experiences for their virtual own body and the fake body but not for the object (Fig.13, Fig.14).

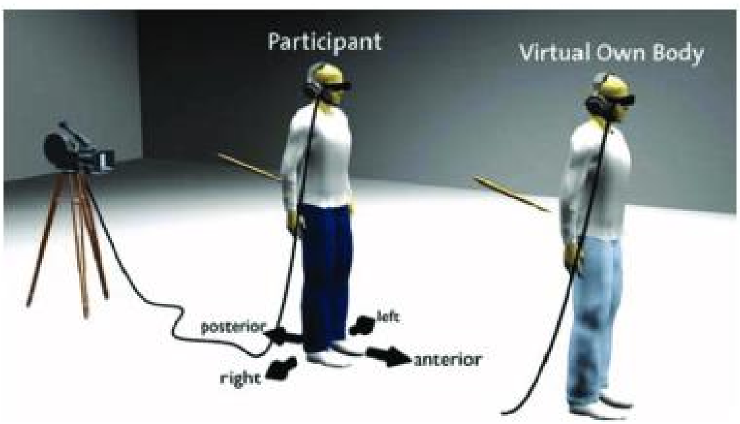

Figure 12. Full Body Illusion Paradigm

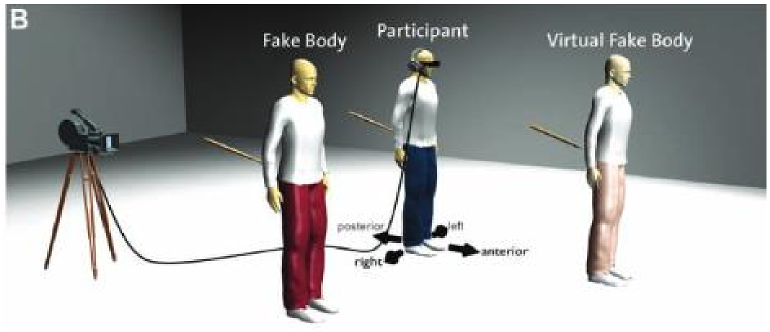

Figure 13

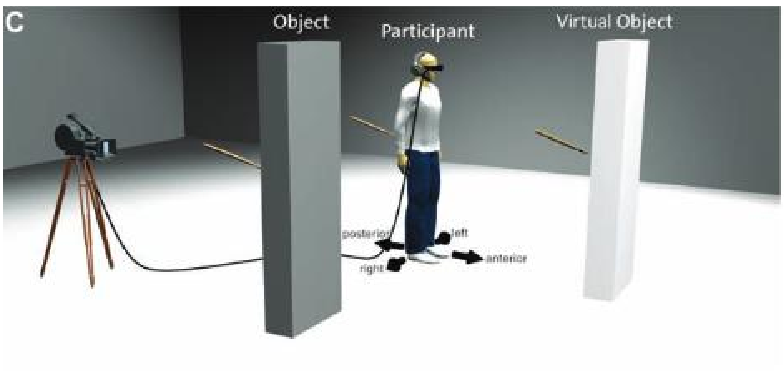

Figure 14

Moreover, in the literature, FBI is accompanied by physiological changes with studies showing higher skin conductance responses as a reaction to full body illusion(Ehrsson, 2007). Interestingly, studies show also that FBI is associated with pain perception increasing the pain threshold (Hänsel et al., 2011). Another study, conducted by Salomon and colleagues 2013 showed that participants' temperature decreased in different body parts on the synchronous condition. Generally, these results indicated that FBI alters bodily self-consciousness and consequently evokes physiological changes.

1.2.14. Temperature Alterations and Body Ownership

As mentioned above, body ownership is a component of multisensory integration of internal and external information. Among those signals, temperature may significantly contribute to the sense of ownership (Crivelli et al., 2023). In order to better explore the role of skin temperature on body ownership and body awareness, several studies have been conducted in the last few years. A study by Crivelli and colleagues in 2021 in healthy participants, aimed to investigate the relationship between body ownership, thermoregulation, and temperature sensitivity. The authors used the

Mirror Box Illusion Paradigm (MBI) (Medina et al., 2015) to moderate the sense of body ownership and investigate the impending changes in body temperature and thermal sensitivity. The use of MBI was for the alteration of body ownership, while for the exploration of changes in body temperature, an infrared thermometer before and after each condition of the MBI. Furthermore, to test the thermal sensitivity, they administered warm and cold stimuli in the hands of participants. The results showed an induction of the illusion of body ownership, participants were susceptible to the illusion of MBI, more in the synchronous condition. This pattern was supported also by a reduction in the skin temperature for both hands in the synchronous condition. Participants also showed reduced thermal sensitivity by perceiving warm stimuli. The authors interpreted these results along the lines of how important is the integration of stimuli to obtain a concrete sense of body ownership (Crivelli et al., 2021). Another case study by Van Stralen and colleagues 2013, included a patient with a right hemispheric sensorimotor ischemic stroke and some problems of body ownership on her left arm more specifically the patient was diagnosed with somatoparaphrenia (Van Stralen et al., 2013). In this study, the method used the Rubber Hand Illusion Paradigm (RHI) (Botvinick & Cohen, 1998) and the measurement of the hand's temperature. Moreover, a questionnaire to measure the subjective illusion was administered. The results showed that for all the measures the RHI was stronger for the contralesional hand compared with the normal right hand. Body ownership deficits were so deep that the proprioceptive drift and the ownership towards the rubber hand were present in both synchronous and asynchronous conditions but only for the left arm. Also, the hand's temperature decreased for the left arm after the induction of the rubber hand. This evidence is supported by the existing literature supporting temperature modulations in the disturbance of body ownership (Moseley et al., 2008; Van Stralen et al., 2013). Crivelli and colleagues using MBI tested the hypothesis of whether a reduction of hand temperature follows the alterations of body ownership. The results showed decreased hand's temperature for the left hand(Crivelli et al., 2023). Finally, Salomon and colleagues (2013), conducted a study to investigate the association between body ownership and skin temperature reduction. The full-body illusion paradigm was used, and indeed the results showed decreased skin temperature across several parts of the body when participants showed a sense of ownership for a virtual body (Salomon et al., 2013).

1.3. Motor Expertise and Body Awareness

1.3.1. Spatial Representation in Musicians

Body representation is a mental representation of one's own body (De Vignemont, 2010). As mentioned above, one of the main properties of body representation is its flexibility to adjust according to changes(De Vignemont, 2010). Although there is experimental evidence that body representation can include non-body parts too, like objects of the peripersonal space, this view remains controversial. For example, musicians may integrate their instruments into their body representation, extending their peripersonal space to include their instruments (Rademaker et al., 2014). An important aspect is the body matrix which integrates multisensory information about the body representations, somatotopic maps, and spatial information about the peripersonal space and receives several sensory inputs such as tactile and proprioceptive inputs. The body matrix is body-centered and thanks to that it can maintain its representation regardless of the location of the limbs. Interestingly, the body matrix creates a functional connection between the body representations, spatial representations, cognition, and emotions, connections very crucial to explain what happened in the case of musicians, dancers, or athletes when it comes to the body representation and multisensory integration(Ladda et al., 2020). Although the body matrix neural network is not explored enough, it is considered that brain areas such as the intraparietal sulcus are highly involved with the body matrix network to be quite adaptable. The intraparietal sulcus and lateral prefrontal cortex are also involved in multisensory integration, and especially the intraparietal sulcus plays a role in generating movements(Bowling et al., 2019; Ladda et al., 2020). Furthermore, it is interesting to examine this evidence in the population of musicians and dancers because these individuals undergo training that requires high motor and sensory skills directly related to body matrix and body and spatial representation domains. For instance, musicians usually create strong relations between movements, sounds, emotions, cognitive processes, and the corresponding neural networks. These mechanisms after repetitions are enhanced by building more reliable associations and might lead to stronger neural correlations (Ladda et al., 2020; Wallwork et al., 2016).

It might seem irrelevant to find associations between music and spatial representation however musical notes are coded in a spatial position both on the paper and on the musical instrument giving strong evidence that musicians train their spatial representation more than non-musicians (Lega et al., 2020). Moreover, spatial attention in musicians seems to be more balanced than in non-musicians especially if they practice on a bimanual instrument since early childhood (Patston et al., 2007). In the case of piano, they equally extend their movements and fingers on both sides and in this way, they shift their attention to both sides through the space (Patston et al., 2007). Moreover, in musical notation, the music writing includes spatial components. Also, an activation of the superior parietal cortex was recorded possibly linked to enhanced visuospatial attention in musicians (Stewart et al., 2003). By looking into the application of music in the clinical domain, studies have shown that playing music can improve left unilateral spatial neglect (Bernardi et al., 2017). Patients with unilateral spatial neglect fail to explore the contralesional side of their body, the space, and their peripersonal space. This deficit is due to lesions in the right parietal lobe (Bernardi et al., 2017). This is based on the statement that the mental representation of space shares common brain networks with other domains such as time, number, and auditory pitch(Bernardi et al., 2017). Results, from a study in patients with unilateral spatial neglect, showed that performing music scales with congruent sound can preserve the auditory and spatial representations of successive sounds thus it might facilitate patients to explore the space on the affected side as well, especially during the musical production from the right side to the left side (Bernardi et al., 2017).

1.3.2. Brain Plasticity in Musicians

As mentioned above, motor expertise can lead to an advantage for spatial representation. Also, neuroimaging studies have been exploring brain changes as an outcome of extended exposure to musical training. Those two dimensions may provide evidence of whether structural and behavioral changes in musicians may contribute to a more coherent bodily self-awareness (Pyasik et al., 2019). First, it is important to present the process following the execution of sequential movements in the case of musical training. Playing a musical instrument is a multisensory motor experience, among the most complex motor tasks (Meister et al., 2004; Schlaug, 2015). More specifically it includes the transformation of visual stimuli like written notation into motor movements (Schlaug, 2015; Stewart et al., 2003). Since musical training is a complex skill, the acquisition and especially the maintenance of this ability, requires that people start playing a musical instrument from an early age in early childhood, and they keep practicing across their lifetime(Schlaug, 2015). Musicians need to integrate high-speed sequential movements with their hands and functionally integrate motor and sensory skills. At the same time, musicians are capable of perceiving other features of music such as pitch or rhythm (Meister et al., 2004; Moore et al., 2014; Schlaug, 2015; Zhang et al., 2015). Studies on developmental psychology linked to musical abilities showed the magnitude of musical training since early life. More specifically the concept of absolute pitch refers to the ability to re-production a musical note without a reference tone (Schlaug, 2001). This ability disappears without music training by the age of 6 or 7 years old. This is evidence that musical skills should start to develop in early life. Generally, it is beneficial to start music training early, however, studies have shown that adult non-musicians who trained in playing piano showed better performance in reading and playing music together with a cortical brain reorganization (Pascual-Leone, 2001; Stewart et al., 2003).

It is well known that brain plasticity is fundamental to human brain function as it responds to environmental input and changes. Brain plasticity supports learning new skills too such as playing a musical instrument. Since the 20th century, scientists have demonstrated the biological power of music training on a neural, anatomical, and structural level as well as in the cognitive and behavioral factors. Several neuroimaging studies have been conducted to investigate the changes in brain plasticity caused by musical training (see fig.15)(Elbert et al., 1995; Schlaug, 2001; Zhang et al., 2015). MRI studies showed that in musicians the left finger representation in the primary somatosensory cortex was larger and the cortical responses increased compared to non-musicians(Schlaug, 2015). These results suggest that the reorganization of the cortical representation for some body parts depends on the use and the current experiences and needs of the individual (Elbert et al., 1995). Also, an increase in sensory receptive field sizes has been reported in professional violinists for the left-string playing hand (Elbert et al., 1995). Other neuroimaging studies showed that the association learning through music can enhance the connection between the auditory cortex and motor cortex and more specifically at the level of arcuate fasciculus. According to MRI studies results, musicians showed differences in the arcuate fasciculus compared to non-musicians (Schlaug, 2015; Wan & Schlaug, 2010). Moreover, it has been demonstrated higher activation in areas responsible for multimodal integration such as the intraparietal sulcus and superior temporal gyrus. Anatomical changes have been captured in the size of the corpus callosum between musicians and non-musicians (Schlaug, 2001; Wan & Schlaug, 2010). Additionally, according to behavioral studies, musicians have better motor skills in tasks that are relevant to music as well as ones that are not while they also show better tactile spatial acute perception (Hirano et al., 2020). Since music and music training are well linked to movements and programming of movements, the motor cortex generally, the premotor area, and the supplementary motor area are highly involved in the execution of any movement(Meister et al., 2004). An fMRI study conducted by Meister and colleagues in 2004 underlined a bilateral activation of the frontoparietal network, activation of premotor areas, the precuneus, and bilateral activation of the posterior parietal cortex. Also, previous studies in adult musicians investigated that after musical training there was a bilateral activation of the superior parietal cortex, an important area for sensorimotor integration (Stewart et al., 2003). Sensorimotor integration in the case of musicians refers to the translation of music notes to movements, and motor responses (Stewart et al., 2003).A voxel-by-voxel morphometric technique implied in musicians who were exposed to musical and motor training and in non-musicians demonstrates structural differences between the two groups. More specifically, they captured gray matter volume differences in the motor, auditory cortex (inferior temporal gyrus), visual-spatial brain areas, and the cerebellum in professional musicians compared to non-musicians (Gaser & Schlaug, 2003; Moore et al., 2014). These data are following previous studies enhancing the statement that long-term musical training can evoke changes at the biological level. Also, more recent studies using various techniques, such as electroencephalography (EEG) and magnetic resonance imaging (MRI), have confirmed and supported all previous results showing how important long-term musical training is for improving sensorimotor skills. It's a process involving functioning integration of sensory-motor information for sensory perception and motor execution (Zhang et al., 2015). In a review study by Moore and colleagues in 2014 they focused on the white matter differences between professional musicians and non-musicians. Concerning the differences is well supported that due to exposure to musical training, the whiter matter fibers across hemispheric connections can alter. Especially, the corpus callosum differences are proven although other cross-hemispheric changes are not always replicated. This evidence creates more space for further research on brain changes after exposure to sensorimotor training such as musical training(Moore et al., 2014). According to other transcranial magnetic stimulation studies woodwind musicians and string, musicians underlined changes in motor maps for the hand representation in the primary motor cortex. However, these changes were captured only in string musicians but not in woodwind musicians (Ginatempo et al., 2021).

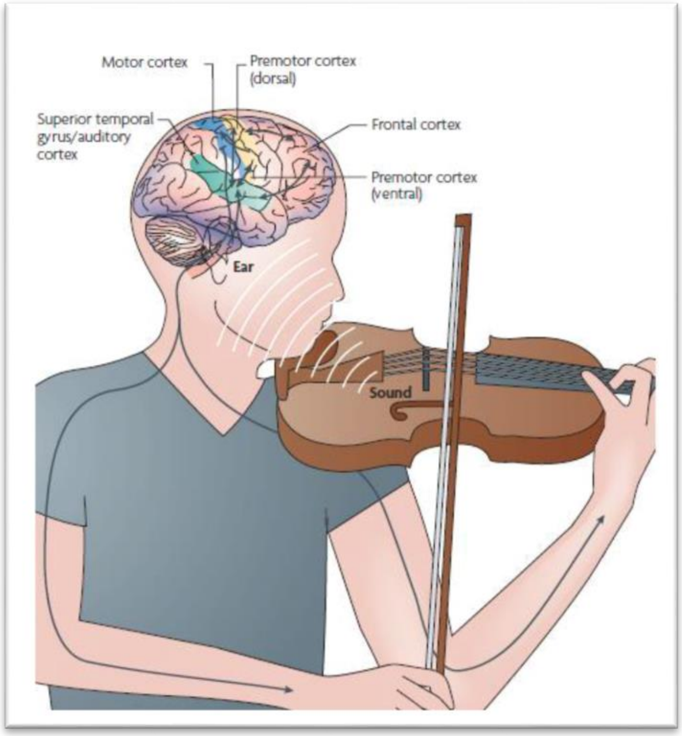

Figure 15. Brain activation in professional violinists

1.3.3. Specific focus: Pianists

As mentioned above, musical training practice is one of the most complex activities responsible for structural and functional changes in the brain. Many neuroimaging studies and reviews focus on the brain changes in individuals who play string instruments. However, few studies are directly focusing on pianists. Exploring musical training in pianists can accurately capture how complex the achievement of playing music is even though musical training is for quite simple music pieces. Pianists need to have complete information about the position of their hand which arises from their body representation and body awareness mechanisms. Also, they receive information about their finger motions and sequence of movements (Pascual-Leone, 2001). According to neuroimaging studies in pianists, the results regarding the reorganization of brain areas follow the general brain changes due to music training. In the TMS study in adults' non-musicians, participants were trained to play a five-finger sequence over five days. The study aimed to investigate the relationship between skill acquisition and the modulation of cortical maps. After they complete the training, results from TMS showed a reorganization of the cortex and greater activation of the primary motor cortex and somatosensory cortex (Pascual-Leone, 2001; Stewart et al., 2003). Moreover, for professional pianists, for example, playing the piano requires the movement of the hand to a target position accurately and controlling fast finger movements. In other words, pianists have better proprioceptive awareness due to the complexity of the musical training since it requires precise finger movements. These raise a possibility that extensive musical training leads to neuroplastic changes in both tactile–motor and proprioceptive-motor integration functions, which has been proven by neuroimaging studies(Hirano et al., 2020).

1.3.4. Movements and Sense of Body Ownership

So far, the main anatomical changes reported and linked to prolonged movements concern the primary somatosensory cortex, the representation of the fingers in the somatosensory cortex, the motor cortex, and motor maps. How can these anatomical changes enhance bodily self-awareness and go beyond the sense of body ownership? This is a topic which is not well studied in literature so far. Initially, is mentioned that brain areas exposed to changes after motor training are mainly brain regions in the parietal lobe, motor, and somatosensory cortex. These areas are highly involved in the bodily self-awareness networks, concerning the evidence that bodily self-awareness includes somatosensory representation and is based on multisensory integration (Berlucchi & Aglioti, 1997; Salvato et al., 2020). In the previous paragraphs, (see "Body Matrix", "Neurocognitive Model of Body Ownership") it has been mentioned that the parietal lobe, especially the temporo-parietal junction, and temporal-parietal sulcus with somatosensory and motor cortex, are highly involved in the multisensory integration process and the maintenance of a coherent bodily self-awareness. These associations between motor expertise and bodily self-awareness neural networks are important for investigating further evidence of whether motor expertise is beneficial for constructing and maintaining bodily self-awareness. Based on several evidence on body ownership modulation, when afferent sensory inputs reach one's own body they are integrated into spatial and temporal domains (Kilteni et al., 2015; Pyasik et al., 2018; Tsakiris, 2010). This perspective is applied in the rubber hand illusion paradigm (Botvinick & Cohen, 1998). Expanding this perspective, it is well known that afferent sensory information arrives both in static conditions and during the movement's execution (Pyasik et al., 2019). Combining all this evidence, the question is whether integrating sensory information during movements can also contribute to the sense of body ownership (Pyasik et al., 2019). Several studies tried to answer these questions by modifying the classical rubber hand illusion paradigm and adding the parameter of passive or active movements (Longo et al., 2009; Tsakiris et al., 2006). However, there is strong heterogeneity in the results from studies that attempted to investigate how the parameter of motor expertise can be linked to the modulation or maintenance of body ownership. For instance, several studies showed that the illusion was equally intense in a static condition and the condition with movements(Kalckert & Ehrsson, 2014), other studies showed that the sense of ownership was decreased due to movements(Walsh et al., 2011), whether other studies increased sense of ownership in the movement condition(Dummer et al., 2009; Tsakiris et al., 2006). Another approach concerns what is happening in the case of absence in movements, and how this absence can impact the sense of body ownership (Pyasik et al., 2019). Studies on clinical populations with paraplegia, tetraplegia(Scandola et al., 2014), and stroke-induced limb paralysis(Burin et al., 2015), patients went through the rubber hand illusion paradigm and the results showed that the patients with tetraplegia did not have a proprioceptive drift, however, they embodied more to the rubber hand(Scandola et al., 2014) and patients with hemiplegia showed a stronger illusion of the hemiplegic hand(Burin et al., 2015). Together these two perspectives concerning the presence or absence of movements provide strong evidence that the factor or movement plays a pivotal role in the sense of body ownership.

1.3.5. Studies in Body Ownership in Pianists

Based on the previous evidence about the contribution of movements in body ownership Pyasik and colleagues (2019) conducted a study to investigate the illusion in a condition in which movements are naturally enhanced and therefore motor-related signals are objectively increased. For this study, the sample was professional pianists and non-musicians (Pyasik et al., 2019). They compared the Rubber Hand Illusion Paradigm (Botvinick & Cohen, 1998) in three conditions (visuotactile, active, and passive movements) in professional pianists and non-musicians. In the visuotactile condition, participants were asked to keep looking at the index finger of the rubber hand and to remain still. Then the experimenter touched both the real hand and fake hand with two paintbrushes synchronously and asynchronously. In the active condition, the index finger of the rubber hand was connected to the participant's index finger with a plastic stick. Participants had to perform a tapping synchronously or asynchronously. In the condition of synchronous stimulation, the participants were asked to tap synchronously and focus their gaze on the index of the rubber hand. In the asynchronous condition, the plastic stick was disconnected in the middle. The participants received the same instructions as in the synchronous condition and the rubber hand was moved by the experimenter. In the passive condition, they were asked to look at the finger index of the rubber hand and to keep their hand still and relaxed. In the synchronous and asynchronous conditions, the process was the opposite of that in the active condition. In both conditions, the experimenter was moving, both the rubber hand and the real hand. The illusion was measured behaviorally through proprioceptive drift and subjectively through questionnaires. The results showed that pianists were less susceptible to the illusion in any of the types of Rubber Hand Illusion. Moreover, pianists compared to the control group did not show any experience of subjective ownership of the rubber hand, or proprioceptive drift. These results demonstrate that the increased number of motor-related signals, afferent, and efferent, affects the construction and the coherence of body ownership (Pyasik et al., 2019).

1.3.6. Studies in the Sense of Agency in Pianists

Both the sense of agency and the sense of body ownership are parts of the complex state of bodily self-awareness (Longo et al., 2008b). The sense of agency is the feeling of authorship over one’s own actions and the control of the execution of those actions(Jeannerod, 2009). In literature, the most implied measure for the sense of agency is the Intentional Binding paradigm introduced by Haggard and colleagues (2002). This paradigm consists in measuring the subjective time of a voluntary action and the sensory events that follow or not that action(Haggard et al., 2002). Pansardi and colleagues (2020), used that paradigm in order to investigate how expert competence acquired through experience, can affect the sense of agency. For this study, they compared the performance of expert pianists and non-musicians. In the study, they used a piano note and an electronic sound. The participants went through four different conditions depending on when they had to do an action or not. For example, in the action-event condition, the participant watched a clock and pressed a button at a freely chosen moment followed by a tone. A participant was asked to report the perceiving time of the tone (Pansardi et al., 2020). Results have indicated that pianists showed greater outcome binding towards both stimuli (note, sound). These results might lead to the statement that musical training might influence the sense of agency because musicians are continuously exposed to the action-outcome associations through training (Pansardi et al., 2020).

1.4. Present Study

After the previous dissertation, we can conclude that bodily self-awareness also relies on somatosensory representations, and according to some evidence, motor expertise contributes to an enhancement of somatosensory cortex representations. At the same time, motor expertise contributes to the reorganization of other brain areas involved in spatial representation. Concerning all these previous insights, this study aimed to investigate differences in bodily self-awareness between a specific population, such as musicians and people from the general population. However, how long-term motor training enhances body ownership is not fully understood. Concerning musicians undergoing prolonged musical training, especially in hand movements, the present study aims to investigate the association of this strong expertise with enhanced bodily self-awareness. The main interest of the present study is the investigation of differences between the two groups after the experimental manipulation of bodily self-awareness. The experimental hypothesis specifically supports that musicians would be less susceptible to MBI in synchronous and asynchronous conditions compared to non-musicians, due to their enhanced manual motor skills. Musicians generally will show less proprioceptive drift, and they will be less affected by the experimental manipulation of body ownership. Alternatively, the null hypothesis supports that there will not be differences between musicians and non-musicians induced by the experimental manipulation of body ownership.

2. Materials and Methods

2.1. Participants

Considering the preliminary nature of the current experimental study, with a sample of 41 healthy volunteers [age range from 19 to 36 years old (M= 23.50, SD= .50), education range from 13 to 18 years; (M= 15.20, SD= .53)] were included in the experiment (30 females with range age 19-31, M=23.10, SD=.83; 11 males with range age 19-36, M=24.70, SD=.86). For the study 26 of the participants were allocated to the control group (non-musician group) while the remaining 15 participants were allocated to the group of musicians. In the control group 5 were males and 21 females, [age range: 19-31 years old (M= 23.30, SD= .97), education range from 13 to 18 years; (M=15.30, SD=.46)]. In the experimental group (musicians) they were 6 males and 9 females, [age range: 19-36 years old (M= 23.90, SD= .37), education range from 13 to 18 years; (M=15.20, SD=.70)]. To include a musician in the experimental group it was mandatory to have an experience of a minimum of five years' experience playing one or more musical instruments, preferably piano as a first or main instrument. All participants gave informed consent before the experiment, and the study was approved by the Ethical Committee of the University of Pavia. All participants in both groups were right-handed. The laterality of the participants was checked through the Edinburg Handedness Inventory (Oldfield, 1971).

2.2. Task

2.2.1. Mirror Box Illusion Paradigm

For the experiment, it was used the Mirror Box Illusion Paradigm, as it was first used by Medina and colleagues (Medina et al., 2015). For the current work, it is specifically used a modified version used in the study of Crivelli and colleagues (Crivelli et al., 2021). According to this, the mirror box consists of a wooden flat board (91.4 cm length x 41.7 cm width). Moreover, two acrylic mirrors (35.5 cm width x 30.3 cm height) were placed in the middle of the board with a 15.24 cm distance between them, following the variation of Crivelli and colleagues (Crivelli et al., 2021, 2023). Participants had their right hand on the right side of the mirror and their left hand on the opposite, left side of the mirror. To minimize the visual information about the actual position of the left arm, a cloak was placed over the subject's left shoulder. On the upper part of the box, perpendicular to the mirrors, a modified meter stick with a length of 15.24 cm was visible to the participants. This ruler was indexed with scrambled numbers preventing the subjects from referencing the actual positions of their hands in the different experimental conditions. In the task, participants were asked to tap with their right and left finger indexes against the mirrors while looking at the reflection of the right hand in the mirror. The left arm was covered during the whole duration of the experiment. This task was formed of two conditions (synchronous and asynchronous). In the synchronous condition, participants were asked to tap against the mirrors synchronously, following a rhythm of 170bmp provided by a metronome. In the asynchronous conditions participants were asked to tap their right and left finger indexes asynchronously, alternating by following the same beat (170bmp). Each condition lasted for '60s.

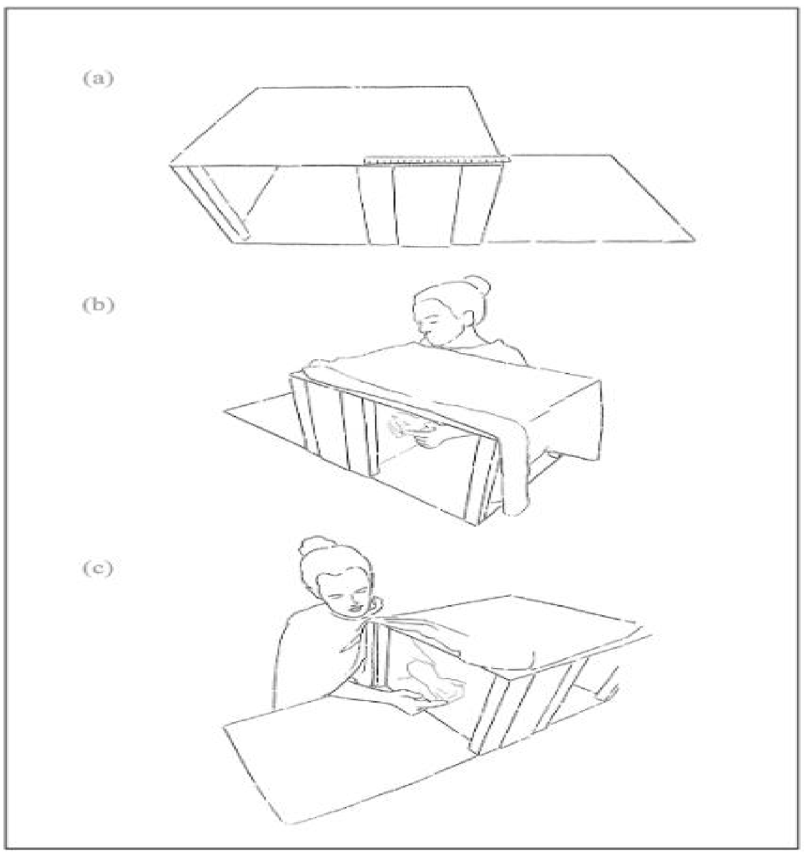

Figure 16. Mirror Box Illusion Paradigm

2.2.2. Tools

Embodiment questionnaire:

To investigate the participants' subjective experience of the illusion and embodiment towards the reflected hand, it was administered at the end of each condition a statement of the Embodiment Questionnaire used also by Medina and colleagues (2015). The questions were nine and they were exploring different parameters such as *location* which refers to the feeling that the mirrored hand and the right hand are in the same position("I felt like my left hand would be in the same position as the hand on the mirror"), *agency* which refers to the sense of having the control of your movements and being able to act ("I felt like I was in control of the hand in the mirror") , ownership which refers to the feeling that the mirrored hand is the right hand ("It felt as though the hand in the mirror was my right hand"), *deafference* which is related to the sense of numbness in ones' hand and the experience of the hand is being less vivid ("It seemed like I couldn't really tell where my right hand was")(Longo et al., 2008a; Medina et al., 2015) .Participants' responses range from completely disagree (-3) to totally agree (+3) on a seven-point Likert scale ranging from -3 to +3.

Extended Barcelona Music Reward Questionnaire:

Concerning the investigation of individual differences in music-related reward, it was administered the extended Barcelona Music Reward Questionnaire (eBMRQ) by Cardona and colleagues (2022). eBMRQ is a self-reported questionnaire formed by twenty-six sentences and involves six main topics: *emotion evocation* ("I like to listen to music that contains emotions"), *mood regulation* ("music keeps me company when I'm alone"), *social reward* ("music makes me bond with other people"), *musical seeking* ("in my free time I hardly listen to music"), *sensory-motor* ("music often makes me dance"), and *music absorption* ("I sometimes feel like I am "one" with the music") (Cardona et al., 2022).Participants can respond following a scale from 1 (completely disagree) to 5 (totally agree).

Goldsmith Music Sophistication Index:

Also, it was administered the Goldsmith Music Sophistication Index for the assessment of musical skills and musical behaviors (Müllensiefen et al., 2014). It is a self-reported questionnaire as well as the eBMRQ. Goldsmith has several subscales which can be used independently from each other. Specifically in this study, it was used one of the subscales, the Perception and production subscale for assessing musical perception and production abilities (Müllensiefen et al., n.d.) composed of 16 questions. Participants can give responses based on a seven-point Likert scale from 1(completely disagree) to 7(totally agree). An example of a question is: “I pass a lot of my free time by doing activities related to music”.

2.3. Experimental procedure

In the study, we had two groups with all the participants participating in both conditions (synchronous and asynchronous). The conditions’ order was randomized, so the order for each participant was different. Before starting the experiment, each participant signed a written informed consent. After the experimenter asked them to remove jewelry from their hands in order to avoid visual information during the experiment. Participants received clear explanations about the purpose of the study and then they were asked to pass the left side of the left side of the box and the right hand on the side of the mirror box. At the same time, after their permission, their entire left arm was covered with a cloak. When participants positioned their finger indexes in the mirror on both sides, they were asked to tell from the ruler with scrambled numbers which number they thought their left hand was. In the synchronous or asynchronous conditions, participants received the instructions to tap on the mirror with their left finger index and right finger index simultaneously for the synchronous conditions or alternating to the beat for the asynchronous condition. A crucial part of the task is that participants while they were tapping, they always had to look at the reflection in the mirror only on the right side. Participants had to keep their focus on the reflection of their hand on the mirror and when they received the instruction to stop tapping, they had to stop by touching their right and left finger indexes on the mirror. Right after, they were asked to indicate from the ruler with scrambled numbers, which number they think their left hand was. Participants had to respond as quickly as possible. In the time between the two conditions, participants completed the embodiment questionnaire and either the eBMRQ or the Goldsmith questionnaires. In other words, participants were asked to point out a number of their subjective experiences with the location of their left arm before starting the task and right after each condition. In all conditions, a rhythm of 170bmp was used provided by a metronome program. All conditions lasted 60 s and to minimize errors, a trial period was provided before each condition of 5s. Overall, the experimental procedure was based on the work of Medina and colleagues (2015) and Crivelli and colleagues (2021, 2023).

2.4. Data Preparation

The participant's responses before and after the experimental conditions about the location of their left hand, from the ruler with the scrambled numbers were transformed into another scale (mm) for the measure of proprioceptive drift. As it was mentioned above proprioceptive drift is the difference between the location of the actual position of the hand and the perception of the location of the hand (Rana et al., 2020). After the transformation, the difference between the after-condition answer and the before-condition answer was calculated. Concerning the eBMRQ for the calculation of the questionnaire, facet scores were obtained from the raw addition of participants' responses to the items. The maximum score is 120. A score lower or equal to 65 indicates music anhedonia, a score higher than 65 and lower than 87 means hedonic, and a score higher or equal to 87 means hyperhedonic (Cardona et al., 2022). For the Goldsmith Music Sophistication Index lower score or higher scores demonstrate a degree of engagement with the music (Müllensiefen et al., 2014). For the calculation of Goldsmith, the score derives from the sum of all the responses.

2.5. Statistical Analysis

Our experimental design is a within-between design 2x2, with two groups and two experimental conditions. For the statistical analysis, repeated measures ANOVA was used to investigate any main effect of the group (musicians-non musicians), any main effect of the condition (synchronous- – asynchronous), or any interaction between the variables of the group (musicians-non musicians) and condition (synchronous-asynchronous). Moreover, to investigate significant differences between the parameters of the embodiment questionnaire (location, agency, ownership, deafference) on the synchronous and asynchronous conditions, a t-test was used. The software that was used is Jamovi 2.3.21.

3. Results

3.1. Demographics

The experiment was conducted with a total sample size of 41 participants. The average age of participants was 23.50, with the average age of female participants (M= 23.10, SD= 2.83), and the average age of male participants (M= 24.70, SD= 4.86). The age range for female participants was 19-31 and for male participants was 19-36. Table 1 below indicates the descriptive statistics and as well as it provides information about the Edinburg handedness inventory. The average education for the participants was 15.20, for the males and 15.3 for the females.

Table 1. Descriptives Statistics

Descriptives

	GENDER	AGE	EDUCATION	Edinburgh
N	0	11	11	11
	1	30	30	27
Missing	0	0	0	0
	1	0	0	3
Mean	0	24.7	15.2	0.873
	1	23.1	15.3	0.841
Median	0	25	16	0.800
	1	23.0	16.0	0.900
Standard deviation	0	4.86	1.40	0.110
	1	2.83	1.60	0.153
Minimum	0	19	13	0.700
	1	19	13	0.500
Maximum	0	36	16	1.00
	1	31	18	1.00

Table 2. Descriptive Statistics

Descriptives

	AGE	EDUCATION	Edinburgh	GENDER
N	41	41	38	41
Missing	0	0	3	0
Mean	23.5	15.2	0.850	0.732
Median	23	16	0.900	1
Standard deviation	3.50	1.53	0.141	0.449
Minimum	19	13	0.500	0
Maximum	36	18	1.00	1

3.2. Proprioceptive Drift

Initially, to analyze the effects of visual illusion on the perceived location of the hidden arm, repeated measures ANOVA was used. This effect has been mentioned as proprioceptive drift. Repeated measures ANOVA with 1-level (condition) and between-subject factors (group) showed a significant main effect of the group factor ($F_{(1,39)}=10.300$; p=.003, $\eta^2p=0.209$) but no significant interaction between condition and group. Musicians showed less proprioceptive drift. Sphericity assumption, Greenhouse-Gesser $\varepsilon= 1.00$. Levene's test is significant for the drift in the synchronous condition (p=.020) so there is a violation in the homogeneity of the available data.

Estimated marginal means show the average value of the variables (condition x participants' group) (Table 3). From the results of repeated measures ANOVA, the interaction between the participants' group and condition is not statistically significant, however, it can be observed in the figure below (Fig. 16) that musicians in both conditions had less proprioceptive drift and the control group showed higher proprioceptive drift in the synchronous condition compared to the asynchronous.

Figure 17. Estimated marginal means.

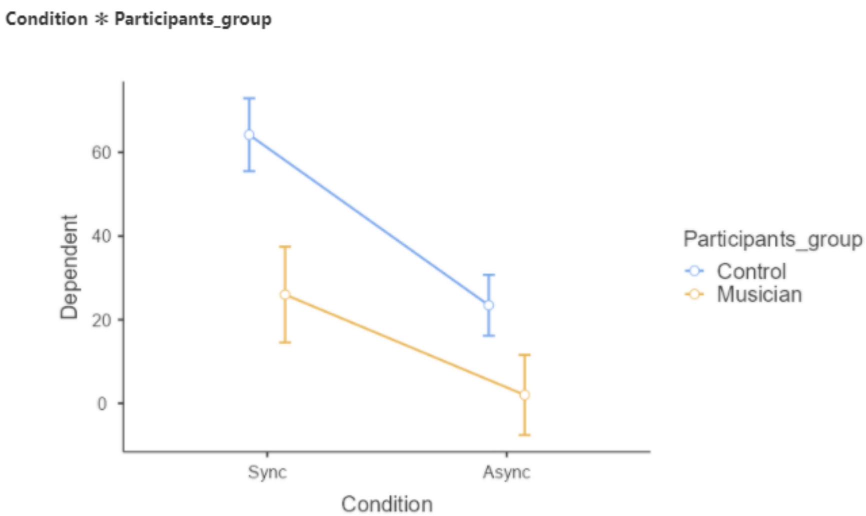

Table 3. Estimated marginal means and confidence intervals.

Estimated Marginal Means - Condition ✻ Participants_group

				95% Confidence Interval	
Participants_group	Condition	Mean	SE	Lower	Upper
Control	Sync	64.23	8.70	46.63	81.8
	Async	23.46	7.29	8.72	38.2
Musician	Sync	26.00	11.46	2.83	49.2
	Async	2.00	9.59	−17.40	21.4

Moreover, the estimated marginal means regarding the main effect of the participants' group captured that musicians' subjective experience about their hidden hand was less affected by the illusion (Fig 17, Table, 4).

Participants_group

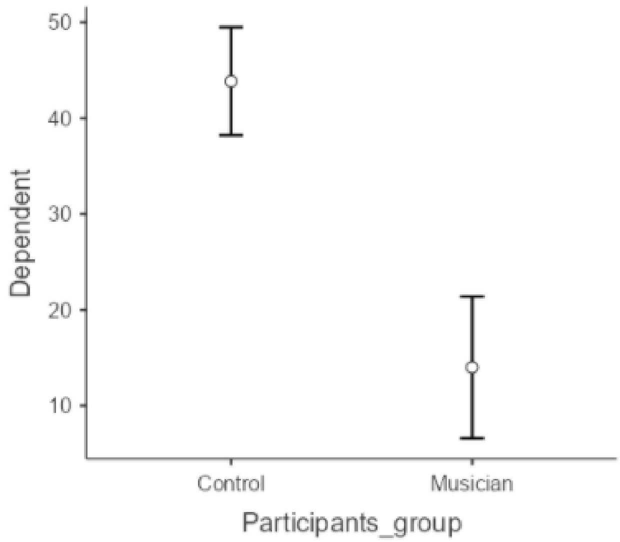

Figure 18. Marginal Means of participants' group

Table 4. Marginal Means and Confidence Intervals

Estimated Marginal Means - Participants_group

			95% Confidence Interval	
Participants_group	Mean	SE	Lower	Upper
Control	43.8	5.62	32.488	55.2
Musician	14.0	7.39	−0.954	29.0

To better investigate further interactions between the participants' group and condition, post hoc comparison tests were used. Internally in the groups, both groups show a significant difference between the conditions. For the control group, there is a significant difference between the two conditions (sync control- async control, p_{tukey}= .005) while for the experimental group, there is no significant difference (sync musicians – async musicians, p_{tukey}= .396). Statistically significant is also the difference between groups (p_{tukey}= .003), confirming the main effect of the group (Table 5).

Table 5. Post Hoc Comparisons

Post Hoc Comparisons - Participants_group

Comparison							
Participants_group		Participants_group	Mean Difference	SE	df	t	p_{tukey}
Control	-	Musician	29.8	9.28	39.0	3.21	0.003

Post Hoc Comparisons - Condition ✻ Participants_group

Comparison										
Condition	Participants_group		Condition	Participants_group	Mean Difference	SE	df	t	p_{tukey}
Sync	Control	-	Sync	Musician	38.23	14.4	39.0	2.657	0.053
		-	Async	Control	40.77	11.5	39.0	3.555	0.005
		-	Async	Musician	62.23	13.0	39.0	4.805	< .001
	Musician	-	Async	Control	2.54	13.6	39.0	0.187	0.998
		-	Async	Musician	24.00	15.1	39.0	1.590	0.396
Async	Control	-	Async	Musician	21.46	12.0	39.0	1.782	0.297

Considering the non-normal distribution a non-parametric independent t-test was used, specifically the Mann- Witney U. Results showed significant differences in both groups for all conditions (U= [102], p=.011 for synchronous, U= [104], p=.013 for asynchronous). Both groups differ in both conditions with musicians having a smaller effect on the illusion in all conditions. Both groups have less proprioceptive drift in the asynchronous condition. The graphs below (fig.18, fig.19) demonstrate these results. Shapiro Wilk test results show that the data do not follow a normal distribution, especially for the asynchronous condition (Shapiro Wilk, p=.093 for asynchronous and p<.001 for the asynchronous condition).

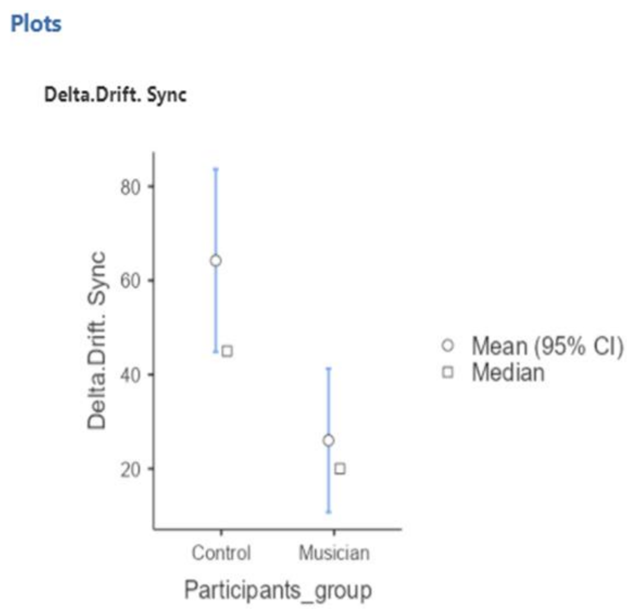

Figure 19. Proprioceptive Drift

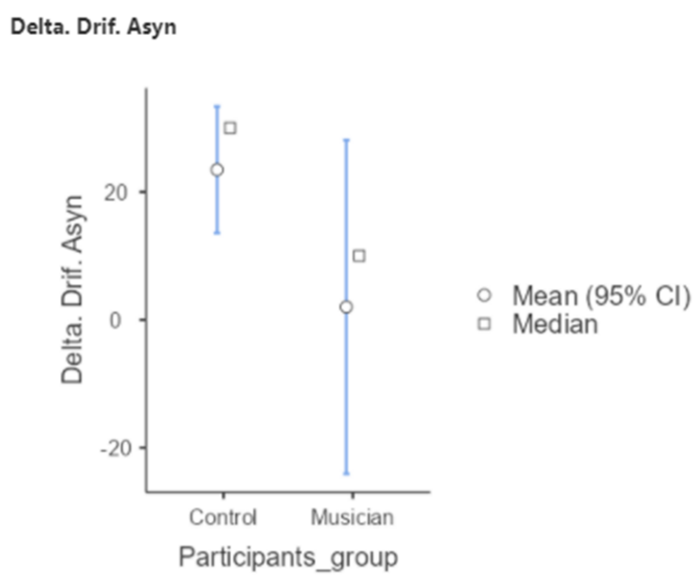

Figure 20. Proprioceptive Drift

3.3. Influence of groups on questionnaire measures

To investigate differences in the parameters of embodiment due to the experimental manipulation of body ownership, an independent t-test was used for each different type of embodiment. To assess the difference in the location regarding the two conditions for both groups an independent sample t-test was used, given that the data follow a normal distribution, Shapiro Wilk p=.098 (for synchronous) and p=.213 (for asynchronous). Results from the t-test (t (39) =2,20, p=.034 for synchronous and t(39)=1,53, p=.0135 for asynchronous) show a significant difference in the location between the groups for the synchronous condition, however, the results for the asynchronous condition are not statically significant (Fig. 20). Musicians have better subjective knowledge about their covered hand position in synchronous condition. To assess the differences in the agency it was used no parametric t-t test (Mann-Witney), Shapiro Wilk p< .001 for both conditions. Results show that there is no significant difference for the agency (U= [183], p=.742 for synchronous, U= [166], p=.432 for asynchronous). For the investigation of significant differences in the ownership component between the two groups, Mann-Witney was used. Shapiro-Wilk, p=. 004 for synchronous and p< .001 for asynchronous. Results show that the two groups do not significantly differ on the parameter of ownership (U= [168], p=.0463 for synchronous and U= [143], p=.0146 for asynchronous).

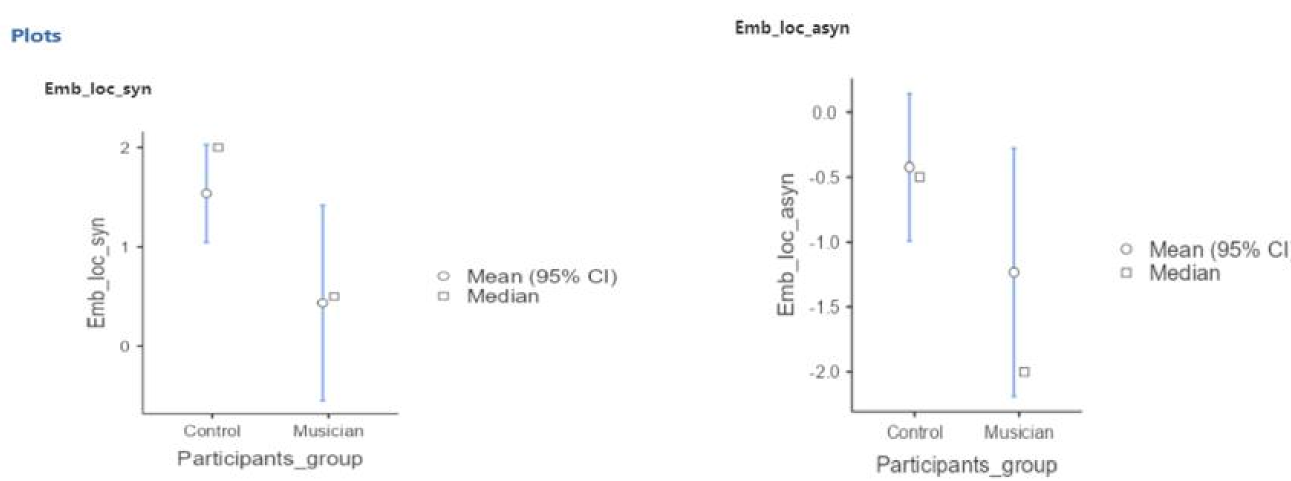

Figure 21. Location

Lastly, to examine differences in the deafference parameter independent sample t-test is used. Results from Shapiro-Wilk (p=.238 for synchronous and p=.074 for asynchronous) allow the usage of a parametric test. T-test results show significant differences in the deafference component, in both conditions $t(39)=2.54$, $p=.015$ for synchronous and $t(39)=3.05$, $p=.004$ for the asynchronous condition (Fig. 21).

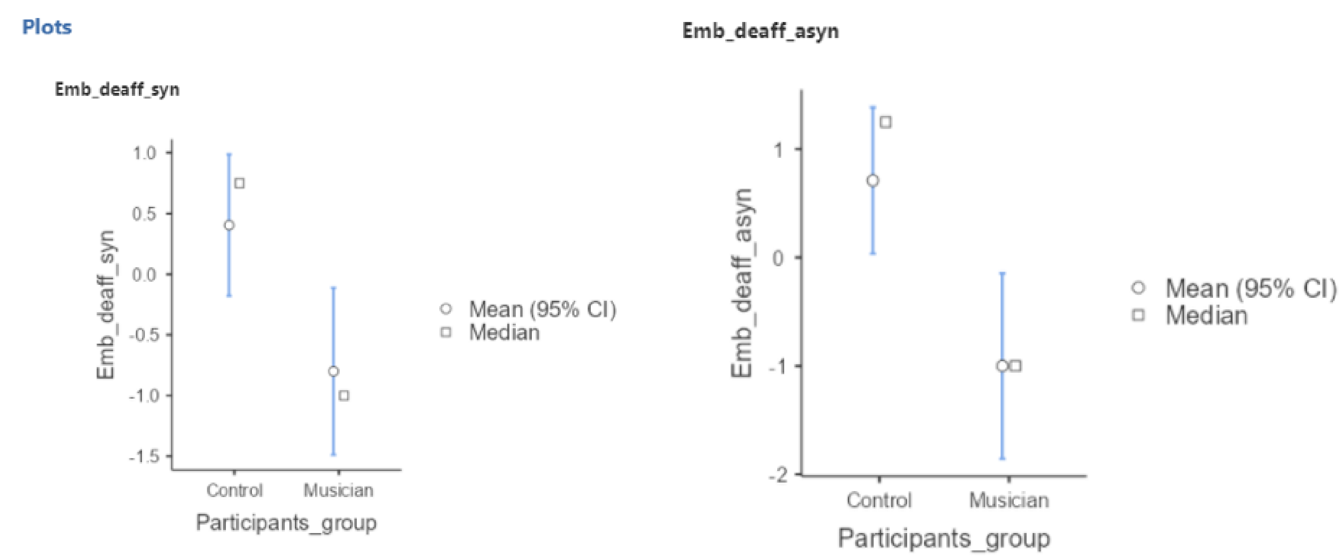

Figure 22. Deafference

3.4. Correlations between musical abilities questionnaires, Proprioceptive Drift, and Embodiment Questionnaire in musicians

To further investigate correlations among the different variables on the questionnaires concerning the Goldsmith and eBMRQ correlation matrix was implied for each participants' group separately., Spearman R was chosen as a correlation index because not all the data follow the normal distribution. Results show that in none of the groups, there is a significant correlation between the drift in synchronous or asynchronous conditions and the tests (Goldsmith-eMBRQ). Especially for the group of musicians the results on the correlation between the proprioceptive drift Goldsmith are $r_s(13)$= [-.090], p= [.749], and ρ= [-.136], p=[.628]. A similar pattern of results is observed in the correlation between eMBRQ and proprioceptive drift. $r_s(13)$= [-.013] ,p=[.964], and $r_s(13)$= [-.201] ,p=[.472].

Moreover, the correlation matrix shows other statistically significant correlations for the group of musicians. More specifically results showed a significant positive correlation between the Edinburg questionnaire and the parameter of location in the embodiment questionnaire for the synchronous condition $r_s(13)= [.583]$, $p=[.023]$. The high score on the laterality questionnaire increases the performance on the location of the left hand in the synchronous condition. Spearman rho showed also a significant positive correlation between the goldsmith questionnaire and the parameter of location for the asynchronous condition $r_s(13)= [.698]$, $p=[.004]$. The high score in the goldsmith questionnaire correlates with better performance on the location of the left hand in the asynchronous condition too. Lastly, a positive correlation between the goldsmith questionnaire and the parameter of ownership for the asynchronous condition $r_s(13)= [.581]$, $p=[.023]$ shows that high performance in the goldsmith correlates with an increased sense of ownership towards the reflected hand in the asynchronous condition.

4. Discussion

The present study aimed to investigate the contribution of movements to the construction of body ownership. For this reason, the experimental group of this study was composed of professional pianists, exposed to extent, musical motor training for a long period of their life. To investigate these differences, a new application of the Mirror Box Illusion Paradigm (MBI) was used following the version applied in the studies of Crivelli and colleagues (Crivelli et al., 2021, 2023). In the present study, the sense of ownership was experimentally manipulated with two different conditions of MBI, synchronously tapping (experimental condition) and asynchronously tapping (control condition) in expert pianists and a control group of individuals without any experience in playing a musical instrument. Then, it compared different aspects of the illusion such as proprioceptive drift and several subcomponents of embodiment. The components that were considered were the location, the ownership, the agency, and the deafference. This study predicted that musicians would be less affected by the illusion and thus they would show less proprioceptive drift after each experimental condition (synchronous and asynchronous). Moreover, it was predicted that differences between groups would be captured regarding the embodiment subcomponents.

4.1. Proprioceptive drift

The first prediction was confirmed since the pianists showed less proprioceptive drift compared to non-musicians. Pianists were not affected by the illusion thus they did not experience the illusion intensively, compared to non-musicians. More specifically, internally to the musician's group, within-group results suggested that musicians did not differ in any of the conditions, for the proprioceptive drift, however internally in the group of non-musicians, post hoc comparisons suggested a statistically significant difference between the proprioceptive drift of the synchronous and asynchronous conditions. For the non-musicians, the illusion through the visuomotor congruence was more intense in the synchronous condition, suggesting that the visual position of the hand strongly affected the estimation of the limb position, especially when the visual input and the motor inputs were temporally congruent (Medina et al., 2015). The proprioceptive drift was higher in the synchronous condition for the group of non-musicians. In our theoretical framework, this result could be intercepted by suggesting that non-musicians tend to perceive their left hand closer to the midline. These results regarding the non-musicians are in line with the results of Medina and colleagues (2015), as well as with the studies of Crivelli and colleagues (2021,2023), and it seems to confirm the statement that multisensory congruence in the MBI paradigm influences the parameters of ownership indicating that subjects tend to perceive the reflected right hand as their left hand (Crivelli et al., 2021, 2023; Medina et al., 2015).

Based on the current results internally in the group of pianists, they did not show a significant proprioceptive drift. According to our theoretical framework these results can be intercepted considering the behavioral and functional changes after the exposure to highly trained motor skills which also are accompanied by changes in neural level (Elbert et al., 1995; Lega et al., 2020; Schlaug, 2001; Stewart et al., 2003). In literature, there is evidence that the estimation of the limb position receives information from different modalities, depending on the precision for each input (Ernst & Bülthoff, 2004). Considering the results from previous studies on the investigation of differences on proprioceptive drift, they showed that individuals estimated better their limb position in the condition with movements, in active conditions, because of the proprioceptive and efferent information (Chokron et al., 2004). This interpretation can be linked to the musician's performance in the current study because all the evidence regarding the behavioral and biological changes in musicians underlined that extended motor skills, and prolonged motor training impact enhancing their proprioceptive abilities. In addition, proprioceptive skills and the integration of other sensory information result in a more robust multisensory integration even though they are exposed to an illusion such as the MBI. The results from the current study can be explained as due to long-term motor practice exposure in pianists. This statement is enhanced by the view that movements can contribute to the coherent sense of body ownership (Burin et al., 2015, 2017; Pyasik et al., 2019; Tidoni et al., 2014). A study in pure hemiplegic patients using rubber hand illusion showed that patients had a weaker sense of body ownership for the affected left hand and more rigid body ownership for the unaffected right hand. These results indicated a possible role of movements in constructing and maintaining the sense of body ownership (Burin et al., 2015).

From a broader perspective, all prolonged and regular motor practice is highly associated with numerous and various afferent and efferent motor-related signals (Pyasik et al., 2019). For instance, due to their motor practice and musical training, pianists' perceptual and motor changes are represented by anatomical and functional changes especially located in the somatosensory and motor cortex, and increased functional connectivity in multisensory and motor cortices (Luo et al., 2012). To support this, a study by Hosoda and colleagues (2016) addressed motor and somatosensory functions in professional pianists, showing that more accurate motor control was positively associated with somatosensory acuity (Hosoda & Furuya, 2016). In the case of the rubber hand illusion application, control participants when they simultaneously received visual and tactile stimuli focused on the visual stimulus, indicating a dominance of the visual stimuli and that's why they fail to recognize the tactile stimulus. Pianists do not experience the illusion showing the absence of the dominance of visual input. Moreover, their motor-related practice requires many years of motor training with a continuous presence of kinesthetic/tactile signals, without a corresponding increase in visual signals (Hartcher-O'Brien et al., 2008; Pyasik et al., 2019). This prevents the dominance of visual information and therefore pianists are less susceptible to the illusion. A similar explanation would be given for the present study since pianists were not susceptible to the illusion in no one of the conditions of the mirror box illusion while the non-musicians were more susceptible especially in the synchronous condition when the visual input and proprioceptive input were temporally congruent (Medina et al., 2015; Meredith et al., 1987).

4.2.1. Location and multisensory integration

In order to subjectively measure the illusion, it was used a readaptation of the measures that Medina and colleagues followed (Longo et al., 2008b; Medina et al., 2015). As mentioned above, there are several subcomponents of the embodiment, such as the location. Location refers to a subcomponent of embodiment, introduced by Longo and colleagues (2008), to describe the sense that the rubber hand was in the same location as one's own hand (Longo et al., 2008b). In the current study, pianists compared to non-musicians had better subjective knowledge of their left-hand position after each experimental condition and more interestingly after the synchronous condition. Instead, non-musicians experienced difficulty in locating their left hand. Thus, they estimate their left-hand position closer to the midline. Specifically, non-musician's responses from the embodiment questionnaire showed that they experienced the feeling that the location of their left hidden hand was closer to the midline. One explanation would be that non musicians based their estimates on the strong visual input leading to the illusion and subsequently causing the experience that the location of the left hand was in the same place as the reflection of the right hand. During the conditions, synchronous or asynchronous, participants were tapping toward the mirror and they experienced a conflict related to the real position of their left hand and the position, where their limb was and where they felt their limb was (Medina et al., 2015). This conflict is stronger on the synchronous condition, as presented in the original study of Medina and colleagues. This would be explained as the temporal congruency of multisensory input providing a stronger experience of the illusion (Medina et al., 2015). The results of the present study are in keeping with previous studies showing a bias towards the visual position in the synchronous condition. For instance, in the original study of Medina and colleagues, results showed increased feelings of location bias affected by the visual position for the synchronous condition and the no movement condition (Medina et al., 2015).

Concerning the musicians several other studies showed an advantage of spatial representation in musicians compared to non-musicians (Bernardi et al., 2017; Lega et al., 2020). In the current study, pianists showed less perceived difficulty of localizing their left hand. Musical training enhances multisensory integration because of the prolonged integration of auditory, visual, and tactile inputs, coordinated with movements (Patston et al., 2007; Pei et al., 2024). Moreover, to support the current results, musicians' enhanced motor skills and in particular the bimanual coordination that musicians have achieved is crucial for the spatial representation. Musicians have developed the ability to perceive their hands in the space without the visual cue making the multisensory integration an independent process to the visual cue. For instance, studies have shown that musicians were more accurate than non-musicians in the line bisection task proving the contribution of musical training in spatial skills (Pei et al., 2024). Together these pieces of evidence would support the present results and explain the difference in subjective experience of location regarding the hidden left-hand in musicians and non-musicians. Furthermore, in literature motor practice seems to be associated with disorders like unilateral spatial neglect. Studies on unilateral spatial neglect and musical expertise provide promising results for the rehabilitation of the disorder through motor training and musical training (Bernardi et al., 2017).

4.2.2. Deafference

Results showed a significant difference between musicians and non-musicians in the component of deafference for both synchronous and asynchronous conditions of the mirror box illusion paradigm. In literature, the sense of deafference has been linked to clinical manifestations and thus it has been explored through patients diagnosed with deafferentiation (Paillard, n.d.). However, deafference is not used only to describe clinical cases but is used as a component of embodiment and it was used to describe the sense of pins and needles, the sense of numbness in one's hand,

and the experience that one's hand is less vivid than usual (Longo et al., 2008b). The significant difference in deafference for the asynchronous condition was captured by Medina and colleagues (2015). Their study showed higher deafference in the asynchronous and no movement conditions (Medina et al., 2015). Moreover, in other studies with intersensory conflict participants experienced feeling like "pins and needles" similar to the feelings after temporal deaffenence (McCabe, 2005). Moreover, in another study with the mirror box, Romano and colleagues (2013) found a decreased kinesthetic sensitivity for the hidden hand when it was passive (Romano et al., 2013). The significant difference in the sense of deafference in the asynchronous condition would be explained by the multisensory conflict of the simultaneous inputs. More specifically, the intersensory conflict arises from the asynchronous visual input versus the proprioceptive and tactile inputs. Thus this conflict can result in the experience of deafference, the sense of not completely perceiving sensory information, in this case, the proprioceptive and tactile inputs (Medina et al., 2015). However, musicians did not experience the sense of deafference and that could be explained by the fact that musical training enhances bodily self-awareness and contributes to a more robust multisensory integration even under experimental manipulation of the sense of body ownership (Hosoda & Furuya, 2016; Pansardi et al., 2020; Paraskevopoulos & Herholz, 2013; Pyasik et al., 2019). Moreover, in musicians due to the neuroplasticity mainly in the somatosensory and motor cortices, they are more able to perceive their limb position, also in the case of a multisensory conflict as in the asynchronous condition of the mirror box illusion. Generally, when the information about the position comes from different sensory modalities, their contribution to the estimation of the position is dynamically weighted depending on the specific input (Medina et al., 2015).

In contrast with previous studies, results showed significant differences in deafference for synchronous and asynchronous conditions. One possible interpretation could be that musicians, due to the neuroplasticity changes, can maintain their body ownership and are aware of the position of their limbs even under experimental manipulation. Another possible interpretation could be the differences in the subjective experience of the illusion. As results have proven thus regarding the objective and the subjective measurements, control group participants were more susceptible to the illusion. For these reasons, it would be reasonable to interpret that the control group experienced the illusion more intense compared with the experimental group so even in the congruent condition the sense of numbness was present to a significant degree.

4.3. Further directions and limitations

Bodily self-awareness is one of the most complex domains. It encompasses a lot of experiences and one of them is body ownership. Body ownership arises from multisensory internal and external signal integration. Motor expertise is a dimension that seems to be related to the construct of a coherent sense of body ownership (Pyasik et al., 2019). The present study aimed to investigate the contribution of movements to the construction of body ownership. The results from the present study are consistent with the literature, underlining the contribution of coordinated movements in the sense of body ownership. Musicians had a better subjective understanding of their limb location and better proprioceptive skills as compared to non-musicians. Musicians' bimanual coordination can be linked to the theoretical framework of bimanual advantage. Indeed studies on pianists and non-musicians showed that pianists were better and faster at tasks that required synchronous tapping (Chang et al., 2014). These results enhance the hypothesis that musicians and, athletes and individuals highly trained in coordinated motor skills are better in tasks requiring the use of both hands. To extend these results musicians have better bimanual coordination suggesting that the increased and coordinated use of both hands provides motor-related signals that enhance body ownership even though without a visual cue. Undoubtedly, this study provides useful insights, although is important to examine these results interpretations and mention some alternative explanations. One possible alternative explanation might be that musicians were less susceptible to the illusion because of the bimanual advantage. To control this parameter as much as possible all the participants underwent the lateralization test of Edinburg. Another possible explanation regarding the difference in susceptibility between musicians and non-musicians might be that pianists have better proprioception as an innate skill. This assumption cannot be controlled, however, there is strong evidence in the literature that long-term motor training causes anatomical and functional changes improving also spatial and proprioceptive skills even in case that individuals start practicing later in life. Moreover, the amount of practice is always an important parameter for achieving such changes.

Furthermore, in this study, some limitations can be briefly addressed. One basic limitation is the sample size regarding the musician's group. To achieve a more representative sample, it would have been better to maintain a better balance between the size of the two groups. Moreover, it could be considered as a limitation that musicians' experience of playing piano had a great variety, a factor that may give less homogeneity to the sample. Finally, the limit of a minimum of five years of experience in playing piano can be a limitation because maybe some other individuals play for less time, however, they follow musical training more intensively.

5. Conclusion

The present study provides important insights regarding the contribution of musical training in multisensory integration processes. Musical training enhances the development and function of specific brain regions such as somatosensory and motor cortices. Moreover, playing a musical instrument improves the performance in many tasks such as motor tasks and spatial representation tasks (Bernardi et al., 2017; Chang et al., 2014; Schlaug, 2001; Stewart et al., 2003). The results from the mirror box illusion showed that motor and hand coordination is crucial to facilitate judgments regarding the limb position. Taking together the subjective and objective components of bodily self-awareness, they provide some evidence for differences concerning the malleability of body representation and body ownership in musicians and non-musicians. This study is consistent with previous studies in literature and underlies the benefits of motor expertise in constructing a more coherent sense of body ownership. Due to the movements, an increased number of afferent and efferent signals together with other sensory information reach the somatosensory and motor cortices contributing to multisensory integration. Thus, the integration of those signals contributes to the maintenance of body ownership. To conclude this evidence is strongly consistent with the fact that humans interact with the environment through the actions of their physical bodies (Gallese & Sinigaglia, 2010). Furthermore, these insights potentially could lead to the further applications of motor expertise in clinical populations such as unilateral spatial neglect. Also, body ownership might be further explored in other highly skilled individuals. For instance, in dancers or athletes. In this case, it would be possible to investigate the ownership of the whole body, rather than only the hands.

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ACKNOWLEDGMENTS

I would like to express my deepest appreciation to my supervisor, Gerardo Salvato, for giving me the opportunity to have my first experimental work.

I especially would like to thank my co-supervisor, Dr. Francesco Crottini for his help, support, and encouragement since the beginning of my work.

I would like to thank my family, my parents, and my siblings. Without their love and their support, none of my dreams would have come true. They are always next to me in any possible way. Their love and support make me feel surer and stronger about every step of my life.

I would like to thank the biggest motivation in my life, my love Alessandro. He always supports me and reminds me that there is always a positive side. Especially, I would like to thank him for being next to me during this difficult year and for encouraging me every day. His patience and trust in me really contributed to this work.

Finally, I would like to thank all my friends who made my two years in Pavia full of joy and happiness. I am finishing this master’s degree and I feel so grateful for all the moments that I had in this city. I feel so lucky to have this opportunity in my life.