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TENS and VR for exploring Bodily Self-Consciousness

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I dedicate this work to my parents and sisters who always believed in me and supported me throughout the process; to my friends, always encouraging, especially Chiara who shared this period with me. I would also like to thank professor Alessandra Pedrocchi who gave me the possibility to spend this time at ETH.
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Abstract

Introduction

Empirical research has shown that the perception that one has of the own body is influenced by the external stimuli presented to him. In this study field, the famous Full Body Illusion (FBI) experiment was conducted involving a subject standing and looking at a mannequin from its back, through a display placed over his eyes. At some point, the individual feels a stroking on his back while contemporary seeing a stick moving on the mannequin's back (Fig. 1): these represent a tactile and a visual stimulus, respectively. It was demonstrated that when these two were synchronized in time, the subject thought that the fake body was his own one, experiencing what is called *Illusory Embodiment*; the same, instead, did not happen when they were not matching in time (asynchronous).

This resulted from the combination of the two stimuli, called multisensory integration, such that the "felt sensation" (stick on the real body) seemed to be caused by the "seen stimulation" (stick moving on the fake figure in front). Thus, it was proved that, adjusting the provided inputs, it is possible to modulate someone's self-perception.

The project introduced hereafter analyzed these concepts, exploring whether other sensory combinations could lead to identical results. Specifically, the same test was repeated but, differently from literature, making use of novel technologies to deliver the stimuli, namely Virtual Reality (VR) and Transcutaneous Electrical Nerve Stimulation (TENS).

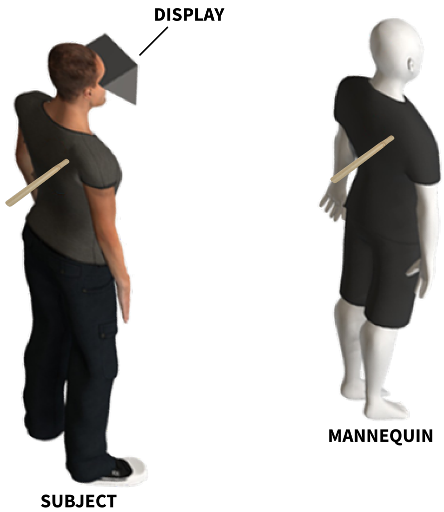

Figure 1: ***Representation of Full Body Illusion experiment***.
Literature experiment developed with a standing subject wearing a display over his eyes in which a mannequin, seen from its back, is represented; as a consequence, he finds himself 2 meters behind the fake figure. At some point, the real subject is touched on his back with a stick (tactile stimulus) and, at the same time, an identical one is moved over the character in front of him (visual stimulus). When these two movements are synchronized in time, the individual thinks that the felt sensation is produced by the stick seen on the mannequin's back and, as a consequence, he has the illusion that the body in front of him is his own one. (Adapted from Nesti, 2018).

Materials and Method

The crucial elements of the used platform were the two new technologies, in fact, its development focused on two main steps: the design of the Virtual Reality (VR) environment and the one of the Transcutaneous Electrical Nerve Stimulation (TENS).
The former is a technology able to generate simulated experience either similar to or completely different from the real world. It was employed for the definition of the surrounding environment: it consisted of a room with simple furniture and a virtual character located in the middle of it in such a way that the real subject was positioned 2 meters behind, seeing it from its back (Fig. 2). The use of Virtual Reality was justified by the huge variable manipulation and control enabled by this system; every detail, indeed, such as objects' position or events' timing, could be finely regulated.
Its realization made use of Unity3D software for the virtual world programming, combined with VR hardware from HTC Vive: a headset placed on the participant head, inserting him in the virtual room, two controllers held in the hands to both localize them and interact with the system and three trackers (two on the feet and one on the chest) to follow these body parts' movements (Fig. 3, panel A).

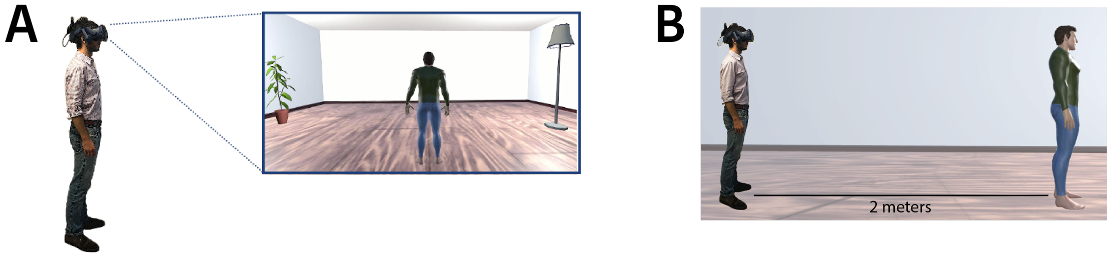

Figure 2: ***Virtual Reality environment***.
In panel A there is an illustration of a subject wearing the headset during the experiment, with the representation of the scene displayed to his eyes. In panel B, an image of the participant taking the test seen from the lateral view is offered, where he is pictured as standing 2 meters behind the avatar.

The latter, instead, consisted of an electric current used to replace the standard touch stimulus, seen in previous studies, because of its being poorly repeatable and controllable in terms of location, timing and intensity. On the contrary, indeed, the electrical signal could be modulated with respect to many parameters (amplitude, frequency and pulsewidth), allowing a fine characterization of the haptic input, able to repeat itself identical over time. This current was delivered using the nerve stimulator RehaMove3: provided with 4 channels, each one connected to a couple of electrodes, it allowed, as a consequence, to contemporary stimulate 4 different locations (Fig. 3, panel B).
The purpose of this project was to demonstrate that the same impact on the manipulation of self bodily perception, observed in literature with a visuo-tactile synchronization, could be reproduced employing a VR-electrical one too.

An additional variable inserted in the protocol was *Movement*: half of the participant took the trial with movement tracking enabled, while the other half had it disabled. In this latter case, subjects were just standing still while in the former one, their actions were followed, thanks to the VR trackers located on their hands, feet and chest, and the virtual body was animated accordingly. As a result, individuals were seeing all their gestures real-time reproduced by the avatar, creating a matching between what they were doing and what they were looking at.
The aim of this condition was to check whether also this visuo-motor synchronization could induce the *Embodiment* feeling.

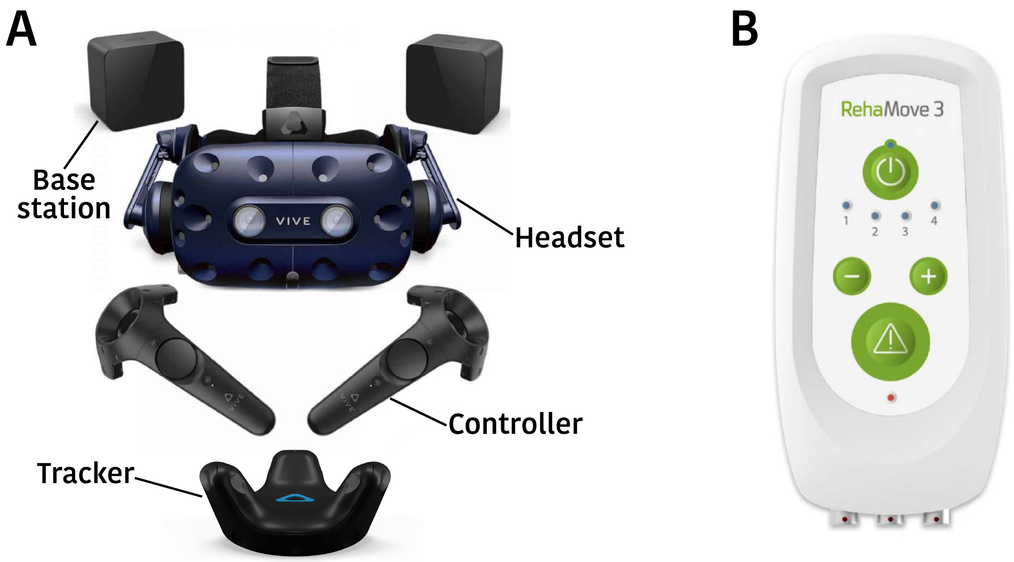

Figure 3: ***Virtual Reality and TENS hardware***.
(A) Representation of HTC hardware: base stations compute the subject's position in the real world, taken as center of the system; the headset puts a display in front of his eyes, enabling to see the virtual environment; controllers are hold by the participant to track hands and interact with the program; trackers placed on feet and chest enable to retrieve their location in space. In (B), instead, a picture of RehaMove3 stimulator device is reported: on the bottom channels, electrodes cables are supposed to be connected.

The evaluation of variables' effects was carried out implementing multiple metrics, both qualitative and quantitative. The former were represented by questionnaires, retrieved from literature, dealing with the concepts of embodiment and consciousness towards the own body. The latter were the self-localization drift, the dominance time in Continuous Flash Suppression (CFS), the level of Skin Conductance Response (SCR) and the Peri-Personal Space (PPS).

All these measures were acquired directly during the VR sessions to avoid any interaction with the real environment that could have added sensory stimulation irrelevant to the experiment.

Gathered data were then analyzed doing comparisons between different stimulation cases, using non-parametric statistical tests (Wilcoxon signed rank and Kruskal-Wallis). These evaluated whether data points could come from the same distribution (indicating the two conditions were similar) or not (meaning that a significant difference existed between the two conditions).

Results and Discussion

In the presented work, the existence of multiple stimuli integrated together was proved to be fundamental for the generation of an illusory embodiment, that is a wrong personification with an external figure. This was possible thanks to an additional tested condition where the subject was just staring at the body in front of him without receiving any input. Resulting ineffective in inducing such phenomenon, this circumstance ruled out the possibility that the only vision of a body in the front space could trigger a mis-identification; as a consequence, it confirmed the essential presence of at least two different signals.

After that, stimuli time congruence was manipulated in order to repeat the same tests already developed in literature: synchronous vs asynchronous. Their outcomes were compared and turned out to be identical: an illusory identification was triggered when visual and electrical stimuli were congruent in time. Obtaining uniform results, it was affirmed that, despite of the technologies used to provide the stimuli, a body illusion was induced just in case these latter were synchronized in time and not when a mismatch was instead present. This finding certified TENS as a valid input in body illusion studies, opening many possibilities for further studies because, being finely controllable and flexible, it allows to overcome the limits of a human delivered touch, encountered while going through literature.

Another investigated variable was the extension of the TENS input: in some cases current was delivered only to 1 limb (right foot), in some others, instead, to all the 4 ones. What was noticed is that a similar Full Body Illusion was induced in both alternatives meaning that no significant impact was provoked by the stimuli size. This is an interesting point as enables to use this platform for people with limb impairments, such as post-stroke patients, for who it may not be possible to have a 4 Limbs stimulation.

Final relevant discoveries regarded movement: actions of the real subject could be either tracked and real-time repeated by the virtual one, or not. The visuo-motor congruence observed in the first circumstance, similarly to the visuo-electrical one, was suggested as a valid trigger for a mis-identification experience with an external body, particularly stimulating a strong sense of agency and control towards it. The same behavior, instead, was not registered in the second situation, where tracking was disabled. The conclusion in this case was that a visuo-motor matching could be used to induce a FBI experience, analogous to a visuo-electrical one.

To conclude, one last situation was assessed where a double synchronicity was inserted: both the electrical and the motion one. However, movement effect was weaker under this circumstance, due to the fact that the Full Body Illusion is a binary event, meaning that, once it is induced with a couple of congruent stimuli, it cannot be enhanced by adding other sensory modalities.

Sommario

Introduzione

La ricerca empirica ha mostrato come la percezione che una persona ha del proprio corpo sia influenzata dagli stimoli esterni che gli vengono presentati. In questo campo di analisi è stato condotto un famoso esperimento, noto come Full Body Illusion (FBI), nel quale un soggetto si trova in piedi e, attraverso uno schermo posto sugli occhi (visore), guarda un manichino di fronte a sé, visto da dietro. Ad un certo punto l'individuo sente un tocco sulla sua schiena e, contemporaneamente, vede un bastoncino muoversi sulla schiena del manichino (Fig. 4): questi rappresentano rispettivamente lo stimolo tattile e quello visivo. È stato dimostrato che, nel caso in cui questi siano sincronizzati nel tempo, il soggetto pensa che il corpo "finto" davanti a lui sia il suo, sperimentando quella che viene definita *Personificazione Illusoria*; la stessa cosa, invece, non avviene quando gli stimoli non sono contemporanei (asincroni).

Questo fenomeno è dato della combinazione dei due stimoli, chiamata integrazione multisensoriale, tale per cui la sensazione "percepita" (bastoncino sul corpo "reale") sembra essere causata da quella "vista" (bastoncino sul corpo "finto", di fronte). Di conseguenza, viene dimostrato come, regolando gli input forniti al soggetto, sia possibile modulare la sua auto-percezione.

Il progetto qui introdotto ha analizzato questi concetti, investigando se altre combinazioni sensoriali potessero condurre a simili risultati. Nello specifico, lo stesso test è stato ripetuto ma, a differenza di quanto fatto in letteratura, sono state utilizzate

Figura 4: ***Rappresentazione dell'esperimento di Full Body Illusion***.
Esperimento di letteratura in cui un soggetto in posizione eretta indossa uno schermo sugli occhi, nel quale viene rappresentato un manichino visto dal retro; di conseguenza, egli si trova 2 metri dietro a questa figura. Ad un certo punto, il soggetto viene toccato sulla schiena con un bastoncino (stimolo tattile) e, allo stesso tempo, un oggetto identico viene mosso sul personaggio davanti a lui (stimolo visivo). Quando questi due movimenti sono sincronizzati nel tempo, l'individuo pensa che la sensazione percepita sia generata dal bastoncino visto sulla schiena del manichino e, di conseguenza, ha l'illusione che questo corpo davanti a sé sia il suo. (Adattato da Nesti, 2018).

tecnologie innovative per fornire gli stimoli, ovvero la realtà virtuale e la stimolazione elettrica transcutanea dei nervi.

Materiali e Metodi

Gli elementi fondamentali della piattaforma utilizzata sono le due nuove tecnologie; infatti, il suo sviluppo si è concentrato su due passaggi cruciali: il design dell'ambiente di realtà virtuale e quello della stimolazione elettrica.
La prima è una tecnologia in grado di generare un'esperienza "simulata", sia simile che completamente diversa dal mondo reale. Questa è stata sfruttata per la definizione dell'ambiente circostante: quest'ultimo consisteva in una stanza con un arredamento semplice e un personaggio virtuale al centro, in modo tale che il soggetto "reale" fosse posizionato 2 metri indietro e lo osservasse dal retro (Fig. 5). L'uso della realtà virtuale è stato giustificato dal fatto che quest'ultima consente un'enorme manipolazione e controllo delle variabili; ogni dettaglio, infatti, come la posizione degli oggetti e la tempistica degli eventi, poteva essere regolata finemente.
La sua realizzazione ha previsto l'utilizzo del software Unity3D per la programmazione del mondo virtuale, combinato con un set hardware fornito da HTC Vive: un visore

Figura 5: ***Ambiente di realtà virtuale***.
Nel pannello A viene raffigurato un soggetto che indossa il visore durante l'esperimento con, a lato, la rappresentazione di ciò che viene mostrato ai suoi occhi. Nel pannello B, viene offerta l'immagine laterale di un partecipante durante il test, nella quale egli si trova in piedi 2 metri dietro all'avatar.

posizionato sulla testa del partecipante, che lo inserisce nella stanza virtuale, due telecomandi, tenuti nelle mani, impiegati sia per localizzare queste ultime nello spazio, sia per interagire con il sistema e infine tre tracker (due sui piedi e uno sul petto) per seguire i movimenti di questi segmenti corporei (Fig. 6, pannello A).
La seconda tecnologia, invece, consiste in una corrente elettrica impiegata al posto dello stimolo tattile standard, risultato essere scarsamente ripetibile e controllabile in termini di posizione, tempistica e intensità negli esperimenti precedenti. Al contrario, infatti, il segnale elettrico poteva essere modulato rispetto a diversi parametri (ampiezza, frequenza e pulsazione), permettendo una precisa caratterizzazione dell'input tattile, in grado di ripetersi in maniera identica nel tempo. Questa corrente è stata erogata attraverso lo stimolatore RehaMove3: essendo fornito di 4 canali, ognuno collegato ad una coppia di elettrodi, consente di stimolare contemporaneamente 4 punti differenti (Fig. 6, pannello B).
L'obiettivo prefissato da questo progetto era quello di dimostrare come, impiegando una sincronizzazione di realtà virtuale e corrente elettrica, fosse possibile ottenere un effetto sulla manipolazione della percezione del proprio corpo, identico a quello osservato in letteratura tramite una coordinazione visuo-tattile.

Una variabile aggiuntiva inserita nel protocollo è il *Movimento*: la metà dei partecipanti hanno svolto il trial con il tracciamento motorio attivo, mentre l'altra metà disattivo. In quest'ultimo caso, i soggetti erano semplicemente in piedi fermi, mentre nel primo le loro azioni venivano tracciate grazie ai tracker della realtà virtuale posizionati su mani,

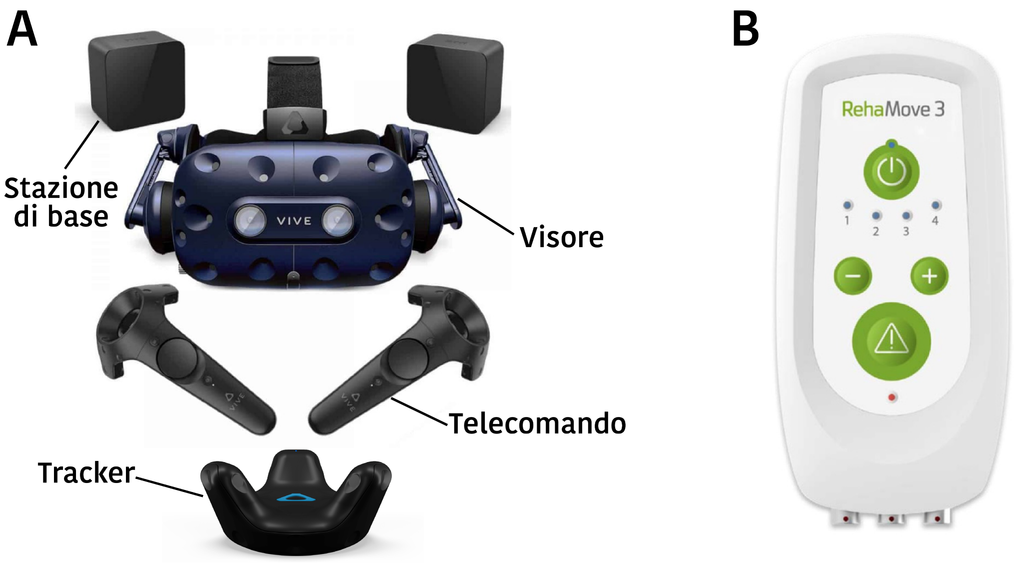

Figura 6: ***Hardware per la realtà virtuale e la stimolazione elettrica.***
(A) Rappresentazione dell'hardware di HTC: stazioni di base per ottenere la posizione del soggetto nel mondo reale, presa come centro del sistema; il visore per far vedere al partecipante l'ambiente virtuale; i telecomandi, tenuti nelle mani, per tracciare il loro movimento e interagire con il programma; i tracker, posizionati sui piedi e sul petto, per ricavare la loro posizione nello spazio. In (B), invece, viene riportata l'immagine dello stimolatore RehaMove3: nei canali in basso vengono collegati i cavi per gli elettrodi.

piedi e petto, e il corpo virtuale veniva animato allo stesso modo. Come risultato gli individui vedevano tutte le loro azioni riprodotte in tempo reale dall'avatar; si creava così una corrispondenza tra ciò che essi facevano e vedevano.
L'obiettivo di questa condizione era quello di controllare se anche questa sincronizzazione visuo-motoria potesse indurre una sensazione di *Personificazione*.

La valutazione dell'effetto delle variabili è stata condotta tramite l'implementazione di varie metriche, sia qualitative che quantitative. Le prime erano rappresentate da questionari, ricavati dalla letteratura, riguardanti i concetti di personificazione e coscienza verso il proprio corpo. Le seconde, invece, consistevano in: auto-localizzazione spaziale, tempo di dominanza durante la Continuous Flash Suppression (CFS), livello di conduttanza cutanea e Peri-Personal Space (PPS).
Tutte queste misure sono state acquisite direttamente durante la sessione di realtà virtuale per evitare ogni interazione con l'ambiente reale che potesse aggiungere stimolazione sensoriale irrilevante per l'esperimento.
I dati raccolti sono stati poi analizzati tramite confronti tra i diversi casi di stimola-

zione, usando test statistici non parametrici (Wilcoxon signed rank e Kruskal-Wallis). Attraverso questi veniva valutato se i dati potessero provenire dalla stessa distribuzione (indicando che le due condizioni erano simili) o meno (segnalando l'esistenza di una differenza significativa tra le due condizioni).

Risultati e Discussione

Nel lavoro presentato di seguito, la contemporanea presenza di più stimoli integrati insieme è risultata essere l'elemento fondamentale per la generazione di una Full Body Illusion (FBI) con una figura esterna. Questo è stato osservato grazie all'aggiunta di un'ulteriore condizione testata, dove il soggetto semplicemente fissava il corpo di fronte a sé, senza ricevere alcun input. Poiché questa circostanza è risultata non essere in grado di indurre una FBI, ha permesso di escludere la possibilità che potesse essere la sola visione di un corpo nello spazio di fronte a sé a stimolare una scorretta identificazione; confermando l'essenziale compresenza di almeno due diversi segnali.
In seguito, la congruenza temporale degli stimoli è stata manipolata così da ripetere gli stessi test già svolti in letteratura: sincrono e asincrono. I loro esiti sono stati confrontati, rivelandosi identici: un'identificazione illusoria veniva innescata quando gli stimoli visivi ed elettrici erano temporalmente allineati. Ottenendo gli stessi risultati, è stato affermato che, indipendentemente dalle tecnologie utilizzate per fornire gli stimoli, un'illusione corporea viene indotta solo nel caso in cui questi ultimi siano sincronizzati nel tempo e non quando, invece, è presente una discrepanza. Questa scoperta ha validato la TENS come input efficace per gli studi di illusione corporea, aprendo diverse possibilità per lavori futuri poiché, essendo finemente controllabile e flessibile, consente di oltrepassare i limiti di un tocco eseguito da un essere umano, già incontrati in letteratura.
Un'altra variabile investigata riguarda l'estensione della TENS: in alcuni casi la corrente veniva somministrata solo ad un arto (piede destro), in altri, invece, a tutti e 4. Ciò che è stato notato è che la risultante Full Body Illusion era simile per entrambe le alternative, dimostrando come la dimensione degli stimoli non provocasse un impatto significativo. Questo aspetto è particolarmente interessante dal momento che consente di utilizzare questa piattaforma per persone con disabilità agli arti, come pazienti

post-ictus, per i quali potrebbe non essere possibile avere una stimolazione completa ai 4 arti.

Ulteriori scoperte rilevanti riguardano il movimento: le azioni del soggetto "reale" potevano essere tracciate e ripetute in tempo reale da quello "virtuale", o meno. La congruenza visuo-motoria osservata nella prima circostanza, simile a quella visuo-elettrica, è risultata un valido innesco per un'esperienza di errata auto-identificazione con un corpo esterno, stimolando in modo particolare un forte senso di padronanza e controllo verso quest'ultimo. Lo stesso comportamento, invece, non è stato registrato nella seconda situazione, dove il tracciamento era disabilitato. La conclusione, in questo caso, era che anche una corrispondenza visuo-motoria potesse indurre tale illusione, analogamente ad una visuo-elettrica.

Per concludere, un'ultima situazione è stata valutata, inserendo una doppia sincronia: sia elettrica che motoria. Tuttavia, l'effetto del movimento in quest'ultimo caso risultava indebolito; questo comportamento è dato dal fatto che la Full Body Illusion è un evento binario, il che indica come, una volta indotta con una coppia di stimoli conformi, non possa essere aumentata aggiungendo altre modalità sensoriali.

Chapter 1

Introduction

The project introduced hereafter presents a reproduction of the Full Body Illusion experiment found in literature, revisited using novel technologies, namely Transcutaneous Electrical Nerve Stimulation (TENS) and Virtual Reality (VR).
The Full Body Illusion (FBI) is a famous experiment traditionally carried out with a participant standing and looking at a mannequin in front of him, seen from behind, through a screen placed over his eyes. At some point, the subject feels a touch on his back, provided by the experimenter with a stick, while contemporary seeing the character in front of him being touched with an identical object (Fig. 1.1). The outcome of these stimuli combination is the development of a feeling of ownership towards the figure in front, so that the individual starts thinking that the fake body he is looking at is his own one; this event is usually addressed as "mis-identification".

Focusing on the trial and its reproduction, the current work deals with the perception of the own body and the level of awareness shown towards it, which is addressed as Bodily Self-Consciousness. A possible way to clarify this concept is to interpret it as "embodied sense of self" [44], indicating the subjective experience of using and having a body [3], that strictly depends on the background an individual is surrounded by. In fact, self-consciousness was demonstrated to be the result of a brain integration concerning multiple sensorial stimuli, coming from the internal and external world [2]. This means that every time one perceives something, such as an object, a huge amount

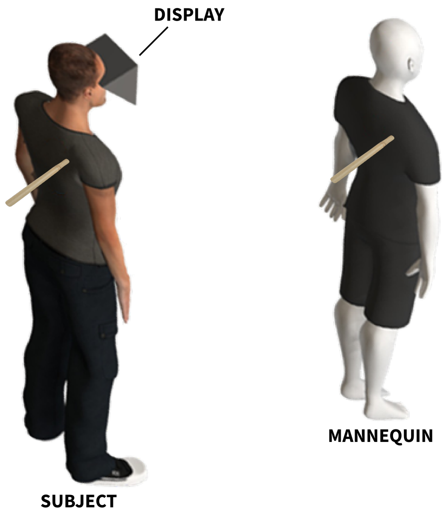

Figure 1.1: ***Representation of Full Body Illusion experiment***.
Literature experiment developed with a standing subject wearing a display over his eyes in which a mannequin, seen from its back, is represented; as a consequence, he finds himself 2 meters behind this character. At some point, the real subject is touched on his back with a stick (tactile stimulus) and, at the same time, an identical one is moved over the fake one in front of him (visual stimulus). When these two movements are synchronized in time, the individual thinks that the perceived sensation is produced by the stick seen on the mannequin's back and, as a consequence, he has the illusion that this body in front of him is his own one. (Adapted from Nesti, 2018).

of inner and outer information are summed together in order to produce a complete elaboration and understanding of the object.

What happens in this case is similar but referred to the own body instead of a generic object: the perception that one has of his corporeal part is the result of an integration of internal and external stimuli. Thus, by understanding how this brain merging process works, it is possible to alter someone's bodily perception by adjusting the stimuli provided to him; the produced effect is termed "Embodiment Illusion". This is a situation where the unity between the body and the self is somehow broken, causing a wrong identification of someone else's body (or body part) as the own one. The term "Embodiment", in fact, indicates the inclusion of an external object in the self-representation. The understanding of this phenomenon and the stimuli combination able to set it up exactly represents the aim of this work. The main hypothesis is:

"Possible manipulation of Bodily Self-Consciousness combining visuo-tactile stimuli: the former produced with a Virtual Reality platform, the latter delivered using Transcutaneous Electrical Nerve Stimulation (TENS)".

Similarly to literature, the final goal is the modification of one's own body representation, through the handling of the provided visual and tactile inputs. However, a difference is introduced in this case, as these stimuli are generated making use of novel technologies:

- the subject's field of view is designed with a Virtual Reality system in which he is completely immersed;
- the perceived haptic feeling is created not with a simple touch but applying an electrical current coming from a nerve stimulator.

The main advantages of these novelties are, on one hand, the flexibility of what can be displayed at the participant's eyes, entirely controlled via software, on the other one, a higher accuracy of the delivered stimulation, compared to a touch from the experimenter used in literature examples. The electrical stimulation, in fact, has a lot of parameters (amplitude, frequency and pulsewidth) that are set through a code, allowing a fine control over the intensity and duration of the final stimulator output.

Various studies on the body illusions shed light on the embodiment notion, analyzing the conditions in which a misguided embodiment, meaning a wrong identification with an external figure, may or may not happen. They showed that it was possible to induce such phenomenon when the two sensory modalities (touch and vision) were synchronized in time; only under this circumstance of visuo-tactile matching, in fact, the brain integration of the two inputs was such that one was confounded about his corporeal figure and lost awareness towards it, personalizing with an external one. These same effects, indeed, were not observed when there was asynchronicity between the two signals, meaning they did not coincide in time.
In this work a similar test is repeated, evaluating the own-body perception after having synchronized external stimuli. As these latter are provided with the novel technologies introduced before, it is better to talk about visuo-electrical congruence instead of visuo-tactile one. Nevertheless, the aim is to check whether same results obtained in literature can be replicated anyways.

Even if it is evident from previous works that multisensory integration of synchronous signals is dominant in the generation of an illusory embodiment, the way in which it contributes to this phenomenon has been debated and, in particular, two different schools grew around this topic. The former, sustained by Ehrsson and other researchers [9], represents the body illusion as an *"All-Or-Nothing"* (AoN) phenomenon, meaning that, once it has been set up, it cannot be enhanced by including additional sensory information. The latter, encouraged by Samad et al. [37], supposes that the induced embodiment changes depending on the amount of available *Sensory Evidence* (SE) and so, the strength of the resulting body illusion can be increased by supplementary sensory inputs.

In future, this experiment could be introduced in the rehabilitation of patients with limb impairments, such as post-stroke ones. These subjects are usually characterized by both motor and sensorial deficits: these latter consist in low awareness towards the own body parts. A recovery could be induced undertaking this protocol because perceiving through the limbs may increase the consciousness level towards them and, in addition, a representation for them is offered by the fact of looking at a similar stimulation over the avatar.

Chapter 2

State of the Art

In past years the possibility of manipulating Bodily Self-Consciousness has been investigated, carrying out experiments able to alter this feeling in order to understand its underlying building blocks and functioning.

2.1 Previous Literature

Different studies regarding corporeal illusions analyzed under which conditions a misguided embodiment could be observed, indicating the wrong feeling that an external body is the own one. The main finding was that it could happen when synchronously triggering two or more sensory modalities (such as touch and vision) both involving a real subject and a mannequin, resulting with an identification of the former with the latter or one of its parts.

Well-known examples of these phenomena are the Rubber-Hand Illusion [4, 10] or Rubber-Foot Illusion [5], referring to body-parts, and the Full-Body Illusion [8, 25], considering the whole physique. In the former case a subject reports ownership towards a rubber limb (hand or foot) located in the position of his own real limb which is, instead, hidden from view; in the latter, the same feeling is expanded from a single part to the complete body and the participant personalizes with a character seen in front of him. In both cases what generates the illusory embodiment is the synchronization of a tactile sensation felt by the subject on his real limb (or body) with a correspondent visual stimulation seen on the fake limb (or body).

2.1.1 Body-parts Illusion

More specifically, in the Rubber Hand (or Foot) Illusion what happens is that the subject's real limb is hidden from his field of view, usually using a box, and a rubber one is placed at its location. Then touch and visual cues are supplied by the experimenter [4, 10] or a robot arm [35]: a wooden stick or brush is moved over the real limb providing the subject with a tactile feeling while, at the same time, an identical stick or brush is passed over the fake limb, giving a visual input corresponding to the felt one (Fig. 2.1). Hence, what the participant is perceiving is identical to what he is looking at but the issue is that, while the feeling is experienced on the real limb, it is seen on the fake one; this confuses him about which one is his own hand. Indeed, it was demonstrated that when these two inputs are synchronized, both in location and time, the subject thinks that the fake hand (or foot) is his own's one [4, 10, 18]. The same illusion is not noticed in the asynchronous circumstance, obtained with the two brushes, one on the real limb and the other on the fake one, moving in an uncoordinated manner.
More specifically, strokes were delivered with a frequency of 1Hz [4]: in 1 second the brush moved down to the hand (from the proximal to the distal part), in the following 1 second, instead, it was detached and returned to the upper position. In the synchronous alternative, the 2 brushes were going up and down together; on the contrary, in the asynchronous one, a delay of 1 second in the movement over the fake hand was inserted so that the 2 brushes were mismatched and when one was going up the other was heading down.
The Rubber Foot Illusion makes use of the same functioning but referred to the foot instead of the hand [5].
As introduced before, the key element in such studies is the synchronization of the visual and tactile stimuli: in these experiments they can be either congruent or incongruent. In the first case there is an accordance between what the subject is feeling

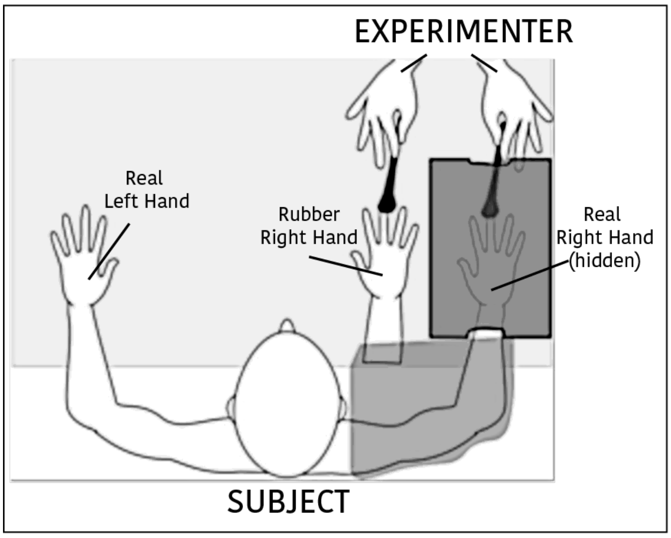

Figure 2.1: ***Schematic representation of Rubber Hand Illusion mechanism.***
The subject taking the experiment is able to see his left hand while the right one is hidden and a rubber right hand is placed at its position. The experimenter (reported in the upper part of the picture) strokes both the real hidden right hand and the rubber one: the first stimulus is the touch felt by the participant (not seen), while the second represents its figurative representation (visible instead). (Adapted from Neustadter et al., 2019).

and what he is seeing in terms of type of stimulation, intensity or time-synchronicity [19, 30]; in the second case, instead, a mismatch is noticed in one of these variables. In the majority of cases time-synchronicity is the altered one [4, 10, 18], with the introduction of a delay between the touch of the stick perceived by the real subject and the vision of the stick on the avatar: this conflict eliminates the incorporation of the fake limb as one's own.

Many reproductions of these experimental manipulations have been performed, trying to improve the setup and better understand the building blocks of the stimuli integration process. In particular, the main goal was to render things in a more automatic and repeatable way [35], so that when a stimulation was repeated different times, all its replicas were identical to themselves.
A possible solution in this direction was powered by the use of Virtual Reality (VR) for the rendering of the visual stimulus instead of a rubber hand or a pre-recorded video of the own limb (sometimes employed in past works). Practically speaking, this meant that the fake limb was created working on a digital platform and then showed to the subject via a head-mounted display (HMD), a sort of helmet with a display in front of

the eyes. One of the major advantages is the huge flexibility in the design of the visual stimulus, having the chance of easily change its properties (size, color, orientation, . . .). Moreover, also a higher control over what the subject is seeing was provided: while wearing the HMD, he was completely isolated from the external environment, with a stronger focus on the scene he was looking at. In some cases, also an acoustic separation was added.

A further upgrade that had been attempted in literature studies deals with the use of a controlled robot substituting the experimenter in providing the haptic feedback [15]. Thus, this latter stimulus becomes more controllable and repeatable for the fact of not being human delivered; in fact, once the robot (or any other kind of programmed stimulator) is set up, the provided feeling repeats identical, while tiny differences can be found (in terms of location and timing) between touches when they are supplied by the experimenter, even if he tries to be as repeatable as possible.

Nevertheless, even if the haptic feelings are always identical, a limitation is still present considering their intensity: being delivered by a robot, they consist of coarse touches poorly controllable. Practically speaking, it means that it is not possible to regulate their strength and type in order to make them as similar as possible to their visual correspondence. This represents one of the main reasons justifying the use of TENS in the current protocol, as it will be explained later (Sec. 3.1).

2.1.2 Full-Body Illusion

Similarly to limbs investigations, also in the Full-Body Illusion the synchronization of tactile and visual stimuli is applied, with one stick moved over the human participant and another one over the avatar; the only difference is observed in their location as they stroke either the back [25] or chest [8] both of the real body and of the fake one. Hence, the resulting feeling of ownership is here reported as referring to the whole body (Fig. 2.2).

Following the same protocol, both synchronous and asynchronous condition were tested in this case too and similar conclusions were drawn [8, 12, 25, 42].

In older studies [8, 25], the sight of the avatar was generated by filming either the subject's own body or a mannequin from a distance of 2 meters in the backspace and

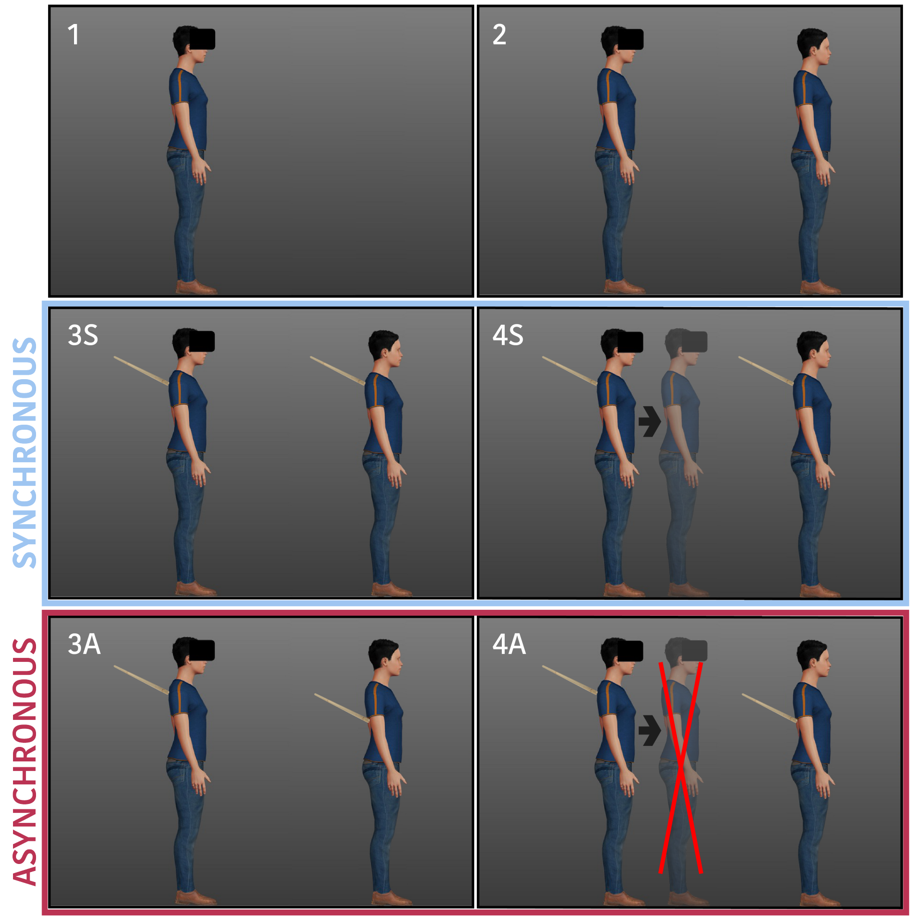

Figure 2.2: ***Schematic representation of Full Body Illusion mechanism****.*
Literature experiments were developed with a standing subject wearing a headset (1) in which the image of a virtual body was represented, so that the subject was seeing an avatar in front of him (body on the right of the image in panel 2). Then the real subject is touched on his back with a stick (tactile stimulus) and, at the same time, an identical one is moved over the virtual body (visual stimulus). These two movements are contemporary in the synchronous condition (3S) while opposing in the asynchronous one (3A). The consequence is that: in the first case, the congruence generates the embodiment illusion, with the individual projecting himself towards the virtual character (4S); in the second one, instead, the same phenomenon is not setup (4A). (Adapted from Salomon, 2017).

reproducing the video onto the Head Mounted Display (HMD) the participant was wearing.

The creation of the synchronous condition was achieved playing this video in real-time; differently, the asynchronous one was obtained by introducing a delay in the video reproduction with respect to the touch provided by the experimenter on the real subject (in this case the video was pre-recorded before doing the experimental session).

Even if whole-body illusions are less diffuse compared to the limb ones, some examples of a FBI reproduction with the use of Virtual Reality can be found as well. To be precise, it is more correct, under these circumstances, to talk about Immersive Virtual

Reality (IVR) [12, 22, 42], as here this technology is not only applied for the avatar's design but for the whole experiment surrounding, with the participant finding himself completely inserted in a computer simulated environment.
Closely to what has been said about limb illusions, also in this case the main advantage was given by the fine manipulation permitted with respect to the tested conditions, as IVR allowed to easily change stimuli properties among them. In addition, this technology made things more interesting and attention-catching for the individual undertaking the experiment, such that he was more focused and responsive [16, 20].

2.2 Literature Limitations

Going through literature works, some limitations were found regarding both the experimental setup and the measures collection [27]. As this project repeated similar tests, it was fundamental to underline these shortcomings in order to avoid them and show the current protocol's benefits.
The dominant drawbacks that were detected are here listed:

1. Experiments with low realism.

   This problem mainly regarded the oldest trials and their inability to render a "realistic" fake limb or body with the consequence of making it harder for the participant to experience an ownership illusion as the item supposed to induce it was not enough convincing both in terms of look and position.
   Recent implementations tried to get over this limitation using VR or IVR, able to represent objects and surroundings in a more natural-looking way, easing both the illusion promotion and the individual attention maintenance;

2. Limited number of considered metrics.

   This issue was encountered in the major part of trials developed in literature where only one qualitative and one quantitative metric were taken into account [25, 8, 42] or, in some cases, just the former one [44]. The direct consequence was that conclusions driven in such way were weaker and less reliable; however, another limit resulted from this, which was the impossibility to compare different measures and shed light over their validity with respect to the experiment and its principles.

This is the reason why the current protocol implemented more metrics, in particular objective ones, as explained later (Sec. 3.1).

3. Inaccuracy in measure collection.

   This limitation was observed with respect to a measure, called self-localization drift, that computes where the subject localizes his physical body in the space. It is collected at the end of each experimental condition, after the stroking session on the participant's back and the avatar's one. The aim was to see whether there was a variation in the self-localization after receiving different stimulations.

   In the experiments where this measure was taken into account [23, 25], it was acquired by blindfolding the subject, so that he was not able to see anything anymore, and displacing him some meters away from his placement; after that, remaining blindfolded, he was required to return to his previous location. The difference between the new position (self-location) and the previous one (real position) was addressed as "proprioceptive drift". (Fig. 2.3). Considering the results, researchers could draw a two-sided conclusion [23, 25]: in the event that the subject located himself closer to the avatar compared to his actual previous position (positive drift), they stated that a Full-Body Illusion was occurring as, by perceiving near the virtual body, the participant was demonstrating a personification with it; in the opposite case where the subject was able to correctly outline his spatial location (drift similar to zero), the interpretation was that he had a complete awareness of his body and no illusion was experienced.

   However, analyzing this measure, the fact that the subject was moving was a limit because this locomotion updated somatosensory and vestibular signals, making it hard to maintain the illusory self-location (in case it was set up) [27]. Thus, the location where the subject identified himself was not only related to the previous occurring or not of the illusion but also to his sense of spatiality. Furthermore, as the subject could move in all directions, a mis-localization could be observed

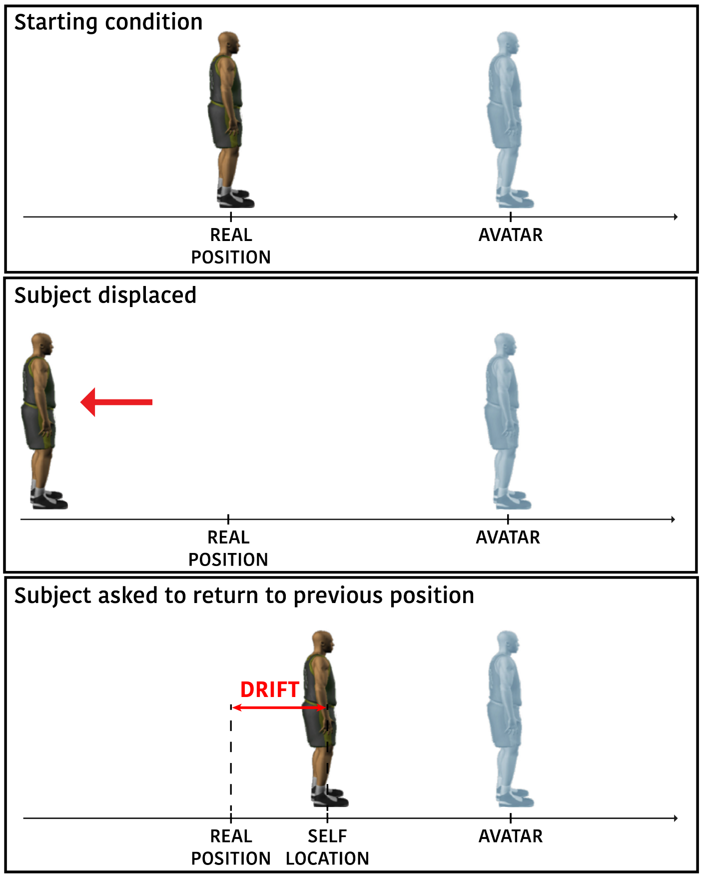

Figure 2.3: ***Schematic explanation of drift measure acquisition seen in literature***. *In the first panel the avatar and the subject are represented; this latter is then displaced in his backspace (second panel) and, after that, asked to return to his initial position (last panel). The term "self-location" is referred to the point in space where the participant re-localizes himself: it does not necessarily match with the real one. In the image, for example, he places himself closer to the avatar and the difference between the real position and the new self-location is called "drift". (Adapted from Lopez et al., 2015).*

on all axis and not just on the anterior-posterior, which is the relevant one considering that the avatar was in front of the subject.

So, a fine control over the computation of this measure was not feasible in this way and, as a consequence, the resulting conclusion were not completely reliable. However, this metric can be an useful tool in this kind of experiments and so, instead of being excluded at all, it should be taken into account but with a better implementation. Considering what was previously underlined, it could be done with the subject not moving during its acquisition and taking into account only the anterior-posterior displacement. To this aim a novel technique had been proposed in a recent experiment [27], which was used in the current protocol too, as explained later Sec. 4.2.1;

4. Effect of the sole vision of the avatar is never evaluated.

   In all the Full-Body Illusion experiments retrieved from literature, the control condition was represented by the asynchronous stimulation that, not being able to induce the embodiment illusion, was used as reference to evaluate results obtained in the synchronous circumstance, instead effective in causing this phenomenon.

   However, as the control condition includes a stimulation too, it is never tested what happens if the subject just looks at the avatar without receiving any kind of stimulation. This represents a big lack conceptually speaking because the real baseline should be the "standard" situation where the participant simply finds himself in the virtual room together with the avatar.

   In fact, without testing this circumstance, it could have been hypostatized that the proprioception cues, generated in the participant by the vision of a virtual body in front of him, were enough to induce the feeling of personification with this external body. In other words, even without receiving any input, just the fact of seeing a character in front could induce the illusory embodiment. As a consequence, the idea that it is the integration of different sensorial stimuli the one able to induce such feeling would fail.

   Therefore, in order to rule out this possibility and demonstrate the importance of multisensory integration, it is fundamental, in reproducing this trial, to test as first thing the effect generated only by the vision of the virtual body;

5. Difficulty in controlling the tactile stimulation.

   In the major part of cases, as it was said before, the tactile sensation the participant felt was delivered by the experimenter, synchronizing or not his action with respect to the video the subject was looking at, depending on the condition he was carrying out.

   It is obvious that a human-delivered touch is really hard to control under different aspects: intensity, timing and location, with a huge lack in terms of repeatability. Therefore, even when the synchronous condition is taking place, meaning that visual and tactile stimuli should be identical, some difference may exist between them, weakening it as a consequence.

   An attempt to solve this problem was tried in successive studies by substituting the experimenter with haptic robots able to deliver a more repeatable stimulation. In the current project an alternative solving was proposed, consisting in the use of electrical pulses which, as well, enabled a fine management over the perceived sensation. In particular, besides being repeatable, this signal could be finely controlled, overcoming the intensity regulation limit encountered when using a robot, as previously anticipated (Sec. 2.1.1). The electrical stimulation, in fact, allows a regulation over 3 different parameters: frequency, amplitude and pulsewidth; as a consequence, the resulting perception is highly malleable and could be adjust to result as similar as possible to its visual correspondence.

Chapter 3

Materials

3.1 Project Novelties

The purpose of the current project is the reproduction of the Full-Body Illusion experiment, developed in literature studies, but making use of new technologies and trying to overcome the previously underlined drawbacks, defining an improved experimental setup.
The main novelties that were introduced are here reported.

3.1.1 Transcutaneous Electrical Nerve Stimulation (TENS) to induce the illusion

The use of a different type of stimulation represents the biggest novelty. In the presented protocol, in fact, the classical back stroking provided with a stick was replaced with an electrical input; in particular, Transcutaneous Electrical Nerve Stimulation (TENS) was selected, which consists in the application of current pulses over the skin using superficial electrodes. In the same way, also the stick seen over the avatar was replaced with a different representation, reflecting the electrical signal; this point will be discussed later (Sec. 3.2.1).
The main advantages resulting from this innovation are reported as follows:

1. Higher control over the stimulation.

   The limitations arising from a human delivered signal, which were highlighted before, were here overcome with the use of this electrical stimulation. Being computationally controlled via a computer interface, it enables to make the resulting feeling repeatable with an accurate control over the timing and location; this latter detail, in particular, is possible thanks to the use of small electrodes. In addition, the intensity regulation limit (still present even when using programmed robots) is removed in this case because a fine regulation of current amplitude, frequency and pulsewidth is allowed, obtaining a precisely defined and detailed sensation;

2. Somatotopic stimulation.

   A peculiar characteristic of TENS stimulation is represented by the fact that it is somatotopic: it means that, even if the sensation is produced through electrodes, the resulting feeling is not perceived just right under them but spreads on a wider area around them. This property can be exploited only with a correct positioning of the electrodes over the target nerve as, in this way, its branches are triggered as well.

   A consequent advantage is the possibility of employing this stimulation also for those subjects with sensorial impairments at their limbs extremities but with intact proximal nerves;

3. Non-invasiveness.

   As it can be inferred from its name, this stimulation is “transcutaneous”, meaning that it is supplied through superficial electrodes over the skin. More than a novelty, this aspect is a benefit which simplifies and speeds up its application as electrodes implantation is not needed. Many times, in fact, TENS application require an invasive approach [34] which reduces its use because more hard and long steps are involved.

3.1.2 Clear control condition: effect of seeing the avatar without the stimulation

This project contained a second control condition, in addition to the asynchronous one also used in literature; it involved the participant simply looking at the avatar in front of him, without receiving any visual or tactile input: he was not touched and no stimulation was provided to the avatar as well. Since only the sight of the virtual body was offered, this condition was called visual-only.
As before mentioned, this condition was needed in order to test whether the body illusion could be triggered by proprioceptive cues, caused by the vision of the own body (or a virtual one) in the same position in the front space. If this was the case, all literature theories, considering the synchronous stimulation as the one able to induce the illusion as opposed to the asynchronous, would be weakened. Therefore, the aim was to rule out this possibility, demonstrating, as a consequence, that multisensory integration of stimuli was needed.

3.1.3 Implementation of multiple measures, both objective and subjective

All the measures employed to evaluate the experimental variables effect were retrieved from published works regarding both FBI and RHI. The novel aspect is that, while literature experiments usually considered couple of them, in this case many different ones were used at the same time, allowing a comparison between them and an assessment of their reliability.
Going into detail, the specific metrics taken into account are outlined below.

The objective ones are:

- Peri-Personal Space (PPS): it is defined as "the space immediately surrounding our bodies" [33]. It represents the space that can be reached with hands or using a tool and is the region where "multisensory integration" of external inputs takes place, indicating where stimuli of different origin are summed together. it means that a subject pays attention to all the events inside his PPS, while ignores the

ones outside.
From literature it is known that when an individual experiences an embodiment feeling, his PPS shifts towards the avatar in front of him [28]; thus, the PPS dimension is a useful tool in this kind of experiments as it correlates with the occurring or not of the illusion;

- Skin Conductance Response (SCR): it is the change in skin conduction capacities connected to the arousal level of an individual and so to what he is experiencing; for example, when someone is scared, his skin conductance increases.
  In the following protocol this value was acquired in relation to a threatening event regarding the avatar (such as objects suddenly hitting him). The underlying concept is that the more the participant was scared by these episodes, the more his SC increased and the higher was the level of identification with the fake body [12, 22];

- Self-localization drift: it determines where the subject perceives himself in space. The idea is that when the subject was able to correctly identify his position in the external environment, it means he had a high awareness of his body and probably no illusory embodiment was taking place; conversely, in case a body illusion was occurring, he was expected to localize himself closer to the virtual character [25]. This mis-localization towards the avatar is known as "proprioceptive drift"; the same phenomenon was observed related to hand localization in the RHI [4];

- Continuous Flash Suppression (CFS) [46]: it consists in a novel metric able to assess the level of awareness that an individual demonstrates towards an object of interest (in this case represented by the avatar).
  During its computation, the interesting item was presented to the non-dominant eye while, at the same time, some flashing colored squares were shown to the dominant one. In case the avatar was predominant over the squares, it meant that it was more significant for the subject and so that a FBI was taking place. Thus, by measuring the proportion of time during which the virtual character was prevailing (called dominance time), it was possible to obtain a proxy of the illusion.

The subjective one, instead, are:

- Embodiment Questionnaire: it regards the embodiment feeling and was realized joining different questions used in literature FBI experiments [12, 13], obtaining a list of items related to the feeling of ownership, embodiment and agency over the avatar. The complete questions set is reported in Appendix A;

- Phenomenology of Consciousness Inventory Questionnaire (PCI): it regards the perception of the own body and was retrieved from a study (Phenomenology of Consciousness Inventory, PCI) proposing a large form; only a part was taken into account, dealing with the level of awareness and consciousness that a person has of his own body as a distinct entity from the external world. The considered questions set is reported in Appendix B.

3.1.4 Evaluation of the effect of the stimulation extension

In the following experiment, differently from what had been observed in literature, the subject was not stimulated on his back but the electrical pulses were given to his limbs and, in the same way, the visual inputs were over the avatar's limbs.
The big novelty here is given by the fact that this new position allowed to modify stimuli extension, by triggering a different number of limbs, and evaluate its effect; specifically, two possible stimuli locations were compared: in one case the subject was receiving current on all his four limbs while, in the second one, only on one foot (in both options the stimulus visual representation on the virtual body was in the same place as the real one).
This alternation permitted to assess whether the extension of the stimulation produced any effect, analysing whether there was a difference in the resulting body illusion between giving inputs to four limbs or just one.

3.1.5 Combination of TENS stimulation and movements

The impact of movement had already been tested in literature both for FBI [12, 14, 22] and RHI [45, 47] experiments: in the first case, by having all participant gestures real-time reproduced by the avatar, in the second one, by moving the rubber hand

accordingly to active movements of the real one. For both, results demonstrated that the insertion of this new variable enhanced the subjective illusory perception that the body (or body part) he was looking at was his own one.
In the reported project the novelty was that the inclusion of movement was coupled with TENS. Practically speaking, participants were divided in two groups undertaking different experimental protocols: one batch performed the experiment with movement tracking enabled, seeing their actions real-time repeated by the avatar; the other one, took it without this additional introduction, just standing still. Results coming from these two different protocols acknowledged both the effect of the sole movement in the FBI induction and its integration with TENS. This latter was possible in those conditions where both were present: in such cases, in fact, they were contemporary, allowing to understand whether their summation could enhance or not the proceeding phenomenon, as it was still unclear from previous works. In fact, this represented a situation where multiple sensory evidences were provided, which outcome had been already debated in literature, with 2 main opposing theories: the *"All-Or-Nothing"* (AoN) and the *Sensory Evidence* (SE) ones. The former thinks that, once the FBI is set up, it cannot be modified adding other stimuli of different nature [9]; the latter, instead, expects that the bigger is the quantity of furnished sensory inputs, the stronger will be the outcome [37].

3.2 System Implementation

The realization process leading to the experimental platform presented as follows can be divided in two main steps: the first relative to the design of the Virtual Reality environment and the second to the one of the Transcutaneous Electrical Nerve Stimulation (TENS).

3.2.1 Virtual Reality (VR)

VR Environment definition

The aim of this step was to build a VR environment in which the classical FBI experiment could be reproduced; thus, the basic idea was to recreate a background resembling the ones observed in literature studies. It usually consisted of a simple room with an avatar in the middle of it and few furniture around in order not to distract the user who was required to focus on the character and the different stimuli provided.
Similarly, in the current trial, the participant wearing the VR system was immersed in a room with wooden floor and a virtual body in the middle of it; around him simple objects (a lamp, a plant, a fan and a painting) were added. Considering the avatar, a standardized mannequin wearing pants and a t-shirt was chosen, and the same character was used for all subjects undertaking the test, without changing its characteristic (such as hair color or size), as it had been observed in literature that these kind of features did not impact the resulting FBI [25, 26]. The only possible adjustment regarded the avatar's sex; to this aim, two different scenes were implemented: one with a male virtual body in the middle and the other with a female one (Fig. 3.1).

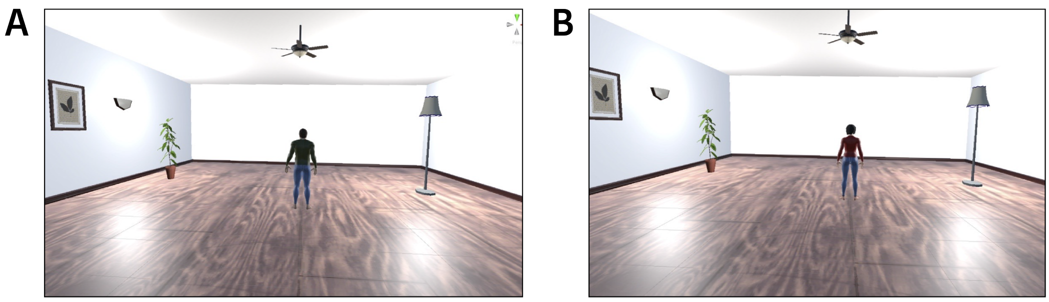

Figure 3.1: ***Scenes screen***.
Screen of both the male (A) and female (B) scene. Apart from the avatar, all the other objects and characteristics (color, position, ...) are identical.

The computational implementation of this scenario was realized completely from scratch using Unity 3D as coding platform, which is a game engine employed to create two or three-dimensional, augmented reality and virtual reality setups. On its main panel (Fig. 3.2, A), on the bottom, there are two windows: one called *Project*, where all the project's elements (objects, characters, scripts, scenes, ...) are listed and one called

Console, where all the messages and errors are displayed while running the code. Looking at the side windows, instead, there is the *Hierarchy* on the left, where every element inserted in the scene, called `GameObject`, is outlined; on the right the *Inspector* in displayed, where all the properties of a selected object are shown (position, size, color, attached scripts, ...).
This software structure is then connected to a Virtual Reality system which allows the subject to enter the VR room through the use of the headset.

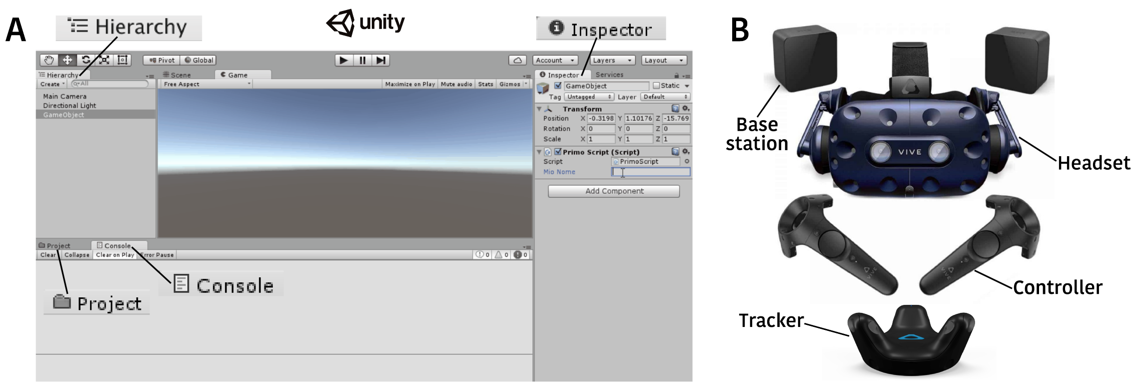

Figure 3.2: ***Software and hardware components*.**
(A) Unity3D screen of how the main software panel appears, with all its components specified (Hierarchy, Inspector, Project and Console); (B) picture of HTC Vive Pro eye main hardware: base stations, headset, controllers and tracker.

In this case the hardware used is HTC Vive Pro Eye, projected by Valve in collaboration with HTC and commercially available, characterized by a headset with high-resolution screen and ear headphones. Furthermore, the system is composed of two base stations for position tracking and two controllers, supposed to be held with hands, used both for experimental interactions and for movement tracking, in case it was required (Fig. 3.2, B).
In addition, in those cases where real-time motion reproduction by the avatar was available, three Vive Pro trackers were utilized (Fig. 3.2, B). Two of them were placed on the participant's feet in order to follow their moves while the third one was located on the chest to get trunk movements. Hand gestures were instead retrieved using the controllers as it had been anticipated before.
Combining together the hardware and the software, the final result is a subject that,

wearing the headset, finds himself placed inside the virtual room with an avatar in front of him seen from its back.

In the following image (Fig. 3.3, A) a representation of the subject undertaking the experiment is reported, including a delineation of the scene he is looking at. In addition, a portrait of the side view is present (Fig. 3.3, B), in which the participant can be displayed as standing 2 meters behind the avatar.

Figure 3.3: ***System functioning***.
In A, Illustration of the subject wearing the headset during the experiment with a representation of the scene displayed to his eyes. In B, picture of the participant taking the test seen from the lateral view, where he can be imagined as standing 2 meters behind the avatar.

The avatar and the other objects inserted in the room were downloaded from the Unity Asset store and then adapted, in terms of size and looking, in order to better fit inside the room. This latter was instead designed from scratch, choosing its characteristics, such as size and colors, in order to look as realistic as possible.

When connecting the HTC hardware and the Unity software, a synchronization step was taken which aimed at centering the real subject inside the virtual room. In fact, his position was tracked, thanks to the HTC base stations, an was taken as center of the Unity environment, so that the individual was in `O(0;0;0)` and everything else could be placed relatively to him. The virtual character was positioned at the same x coordinate as the real one, so that it was centered with respect to the horizontal axis, but 2 meters ahead relative to the z axis, so that the participant was seeing it from its back in the front space, as previously anticipated.

"Visual representation" of TENS

A fundamental advantage offered by the use of VR is the possibility of having a visual representation of TENS. In fact, a difference compared to the traditional experiment regarded the visual counterpart of the haptic stimulation.
In literature reports, what the subject was seeing on the avatar was a faithful reproduction of the sensation delivered to his real body. Here, instead, an identical reproduction was not feasible, given that the electrical stimulation is something not visible in the external world. In this case, what the participant observed on the virtual limbs were some white wavy lines moving downwards (Fig. 3.4).
The visual stimulus was created from scratch and its selection was an attempt of physically representing the electrical stimulation that is something intrinsically not evident from the outside. Thus, the aim here was to find something that could resemble the sensation given by TENS which is a mix of vibration and tingling spreading on the surrounding area.
Without the use of VR, this would have been unfeasible; employing, for example, a pre-recorded video of the real subject, nothing would have appeared over his limbs while receiving the electrical current, removing the visuo-tactile coexistence.
The selected representation had an impact on the homology concept which refers to the fact that what the subject was perceiving on his body was identical to what he was looking at on the avatar's one. While homology was present in the classical stroking, it was not in the TENS alternative; the consequences of this absence and whether it had or not an effect on the resulting FBI will be discussed later in the text Sec. 6.3.

Advantages of Virtual Reality

The decision of reproducing the FBI experiment with a virtual background instead of a real room comes from the awareness of the advantages of using such technology, already demonstrated in literature [16, 20]. In fact, compared to a "physical" scenario, the virtual room is more appealing in the participants' eyes and this was proved to increase their attention to stimuli. Furthermore, the eventual inclusion of movement tracking makes the platform highly interactive, enhancing the feeling of ownership.

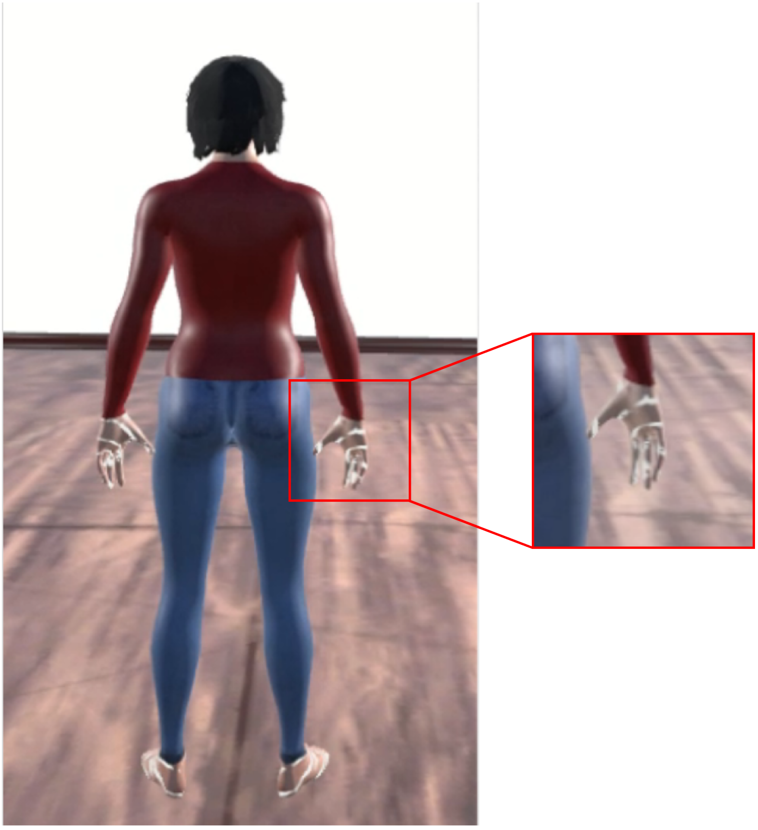

Figure 3.4: ***Visual representation of TENS.***
Representation of the visual stimulation seen on the avatar limbs while feeling the electrical current on the own ones.

In addition, from the experimenter viewpoint, the possibility of managing the environment and all the events occurring in it via a computer allows a fine control over their features, such as timing and location.

Movement Tracking

The introduction of movement tracking is one main hallmark feature of the presented protocol. Its implementation required the use of HTC trackers, which represent the hardware components allowing to trace participants' moves, then connected to the Unity software through the `Animation Rigging` package. It is a specialized craft in the 3D modeling process which provides a library of rig constraints that can be used to produce motion at run-time. First of all, it allows to render the skeleton of the avatar, where every part (such as arm, forearm and hand) is identified with a different segment. Then, among the different possible constraints between these elements, the `Two Bone IK Constraint` was chosen as enables character's limbs to be driven by inverse kinematics. The software/hardware synchronization was done from scratch selecting, for each tracked region, 3 elements, `Root`, `Mid` and `Tip`, as anchor points both position and rotation should be referred to. Three different body segments were chosen respectively, which movements were aligned in order to result as natural as possible; the selected components depended on whether the tracked limb was an upper or lower one:

- for upper limbs: arm was marked as `Root`, forearm as `Mid` and hand as `Tip`;
- for lower limbs: thigh was marked as `Root`, leg as `Mid` and foot as `Tip`;
- for chest: lower back was marked as `Root`, spine as `Mid` and chest as `Tip`.

The last step was the synchronization between this software package and the trackers on the real subject. This was done through a script included in `Animation Rigging`, which aligns the movements of a `VR target` and a `Real target`, inserted as code parameters that needed to be specified. In particular, for the current protocol:

- for upper limbs: left and right HTC controller, held by the participant, were chosen as `VR target` and left and right hands, respectively, as `Real target`;
- for lower limbs: 2 HTC trackers, attached to participant's left and right foot, were chosen as `VR target` and left and right foot, respectively, as `Real target`;
- for chest: a HTC tracker, placed on participant's chest, was chosen as `VR target` and the correspondent chest segment as `Real target`.

Regarding the 3 trackers, a previous initialization step was needed where, via the Vive Pro program, their position was uniquely assigned to one foot or to the chest; in this way, one device was always tracking the same body part.

3.2.2 Transcutaneous Electrical Nerve Stimulation (TENS)

TENS stimulation characteristics

As previously anticipated, the main novelty of the developed platform is the use of TENS, a stimulation based on electrical pulses and thus of a completely different nature compared to the one used in literature experiments. This latter, in fact, was realized with a series of back stroking provided by the experimenter moving up and down a stick; the frequency of the touches was 1Hz and they were repeated for a total time usually around 60 seconds (it had been proved that at least 45 seconds were needed for the FBI onset [5]).

The electrical stimulation, instead, was delivered using the RehaMove3 device (Fig. 3.5, A), a CE approved non-invasive surface stimulator produced by HASOMED (Germany). It uses superficial electrodes (Fig. 3.5, B) that can be placed directly over the skin, without needing a specific preparation, and easily removed at any time. The device has a safety button that allows the instantaneous power-off of the stimulation, a button to switch it on and off and 3 channels on the bottom where electrodes cables are connected. Actually, one of these cables splits in 2 different branches and so, the final number of channels (and of possible stimulable spots) is 4, as reported in the below image (Fig. 3.5, C).

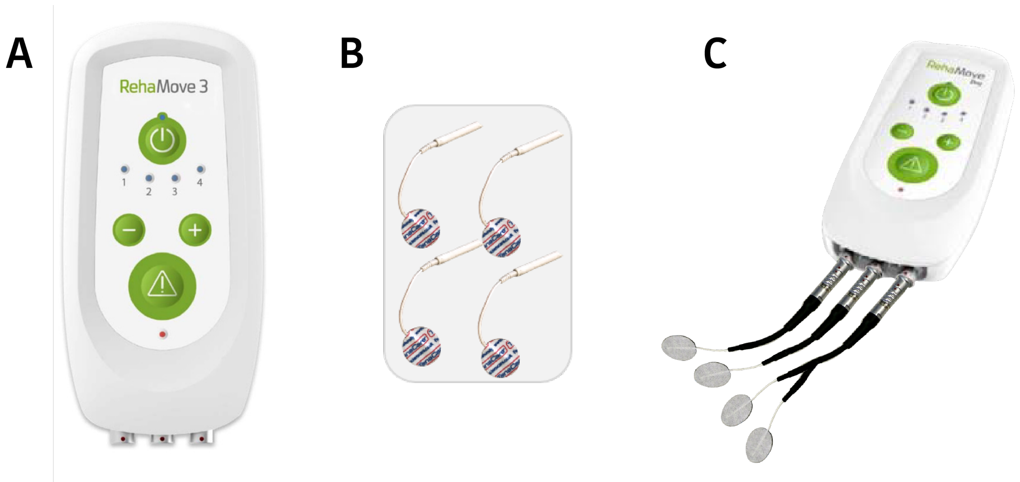

Figure 3.5: ***Stimulation devices***.
(A) RehaMove3 device for TENS stimulation with power on/off button, security button and the 3 channels on the bottom. (B) Superficial electrodes for non-invasive electrical stimulation. (C) RehaMove3 device with electrodes cables attached; as one of them bifurcates, the final number of stimulating channels is 4.

Besides its nature, the employed stimulation had another fundamental difference, with respect to the classical stroking, which was its location; in fact, the sensation was delivered to the subject's limbs and not to the back anymore. To do so, TENS electrodes were placed proximally with respect to the target limb because only in this way the resulting feeling could spread over the whole limb, exploiting its somatotopy. Going into details, the specific locations were:

- hands: electrodes were placed on the wrist, over the median nerve, and the sensation was felt on the palm (Fig. 3.6);
- feet: electrodes were placed on the ankle, over the peroneal nerve, and the sensation was felt on their upper part (Fig. 3.6).

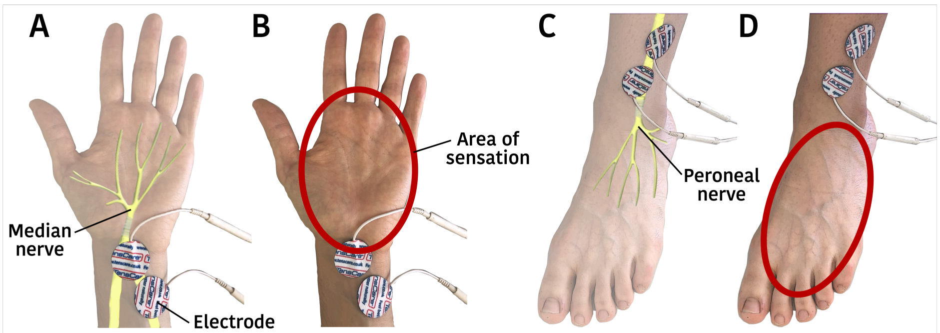

Figure 3.6: *Electrical stimulus location*.
(A) Representation of electrodes placement over the median nerve for hands and (B) approximation of the area where the resulting sensation was felt; (C) representation of electrodes placement over the peroneal nerve for feet and (D) approximation of the area where the resulting sensation was felt.

TENS stimulation definition

The Rehamove3 device functioning was computationally programmed, meaning that all the features (such as duration or intensity) of the stimulation resulting from its activation were pre-defined via software. A basic code for its control had been provided, then modified accordingly to the desired output signal. In the current protocol, a pulsewidth-modulated one was chosen as input, which consists in current pulses characterized by: constant amplitude (based on Calibration results, Sec. 5.1), constant frequency (set to 50 Hz) but changing pulsewidth, varying between a minimum and a maximum according to a Gaussian shape. The consequent perception on the subject's limbs was an electrical feeling with an intensity continuously going up and down in a range; minimum and maximum values were defined before the experiment starting, during the calibration phase (Sec. 5.1).

The single wave was designed using *Matlab*. Its shape (Fig. 3.7) follows a Gaussian course, going from the minimum to the maximum value and then again to the minimum in a time interval of 8 seconds. Then, the curve is completely flat for 2 seconds; referring to the electrical input, it means that during this time interval no current is delivered.

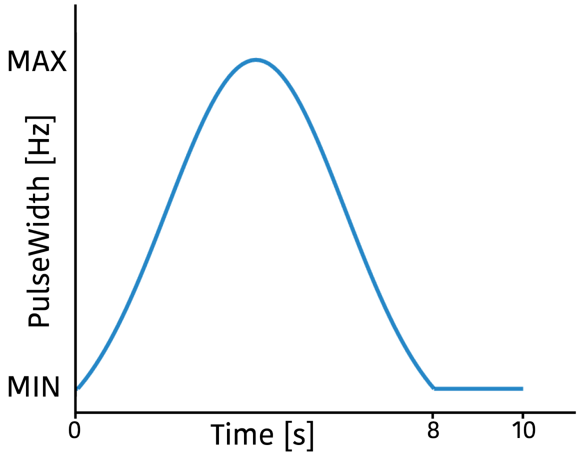

Figure 3.7: ***Stimulation trend***.
Curve of the Gaussian stimulation wave varying between minimum and maximum pulsewidth.

In order to use this wave in the definition of the electrical stimulation, it was interpolated with different points which value on the y axis was normalized to a `[0, 1]` range, corresponding to the minimum and the maximum respectively. These gathered data were then inserted in the stimulator code, in the curve shape definition section, where minimum and maximum pulsewidth levels (found during calibration, Sec. 5.1) were specified too. At each run, the device was reading one value ($value$) and delivering a current which pulsewidth (PW) was defined by the subsequent formula:

$$PW = PW_{MIN} + (PW_{MAX} - PW_{MIN}) * value \tag{3.1}$$

In this way, when the wave was at its minimum ($value = 0$), a current with minimum pulsewidth ($PW = PW_{MIN}$) was given as output; then it was increased until reaching the maximum pulsewidth ($PW = PW_{MAX}$) when the curve was at its maximum ($value = 1$) and, finally, it was decreased again.

During the experimental stimulation step, the wave was repeated 6 times in order to have a total period of 60 seconds, respecting the length of the FBI induction phase found in literature.

This same curve was used for the visual stimulus displayed on the avatar: the white wavy lines on the virtual limbs, in fact, had an intensity varying between a minimum and maximum value following the same Gaussian shape reported for the electrical input, with the same timing too.
Using the same method previously explained for pulsewidth, the intensity of the white stripes was controlled with a `for` cycle, where at each iteration the intensity value was increased or decreased (respecting the same formula reported above, eq. (3.1)) in order to vary between pre-defined minimum and maximum levels. Once the same waveform was chosen for the two stimuli, it was necessary to define when to set them on; here, in fact, uniformly with literature, two possible stimulation patterns were defined:

- Synchronous, where tactile and visual inputs appeared at the same time (Fig. 3.8, A);
- Asynchronous, where just the visual input was shown at the beginning and the electrical one only after a delay (Fig. 3.8, B).

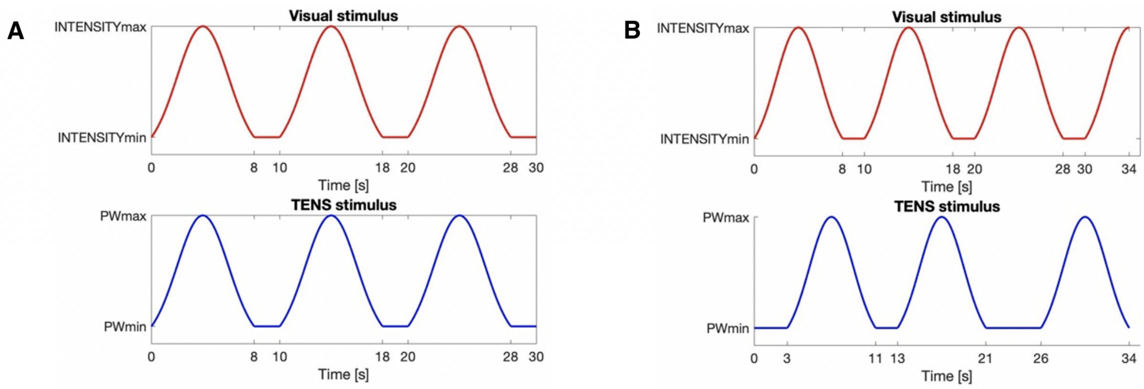

Figure 3.8: ***Visual and electrical stimuli graphs.***
Visual and electrical stimulus waves in the (A) synchronous and (B) asynchronous case respectively.

In the latter alternative, the delay of the electrical input with respect to the visual one was varied in a range from 2 to 5 seconds in order not to cause any kind of correlation between the two waves. In fact, in case the two signals were perfectly opposing (with

one reaching the maximum when the other was at its minimum level), the risk of inducing an inverse synchronization could occur.
From the subject's point of view, the outcome of the asynchronous scenario was a mismatch between what he was feeling on his body and what he was watching on the virtual one, able to prevent the embodiment illusion [35] to set up.

Another variable of the electrical input was its location: indeed, both one and four limbs stimulation was possible. These two modalities were pre-defined with two different scripts, activating a different number of Rehamove channels respectively; then, the selection of which script was to be started, done through the code, depended on the experimental condition that was running.

Chapter 4

Experimental Method

In the current paragraph the procedure followed during the testing is outlined, including the different assessed conditions and the acquired measures. Differently from what was found in literature articles, in this protocol a great amount of stimuli combination, and of subsequent measures as well, was evaluated, allowing to answer various research questions and enabling metrics comparisons regarding their reliability.

The different tested situations were the direct result of combinations mixing the investigated variables, namely: synchronicity (synchronous/asynchronous), number of limbs (one/four) and movement(on/off). All comparisons and relative results reported in the text were conducted during the experimental sessions; no data had been already provided from the laboratory.

Each condition was run separately with a duration of nearly 20 minutes, during which both subject stimulation and all measures acquisition took place. A single condition can be subdivided in different runs, each one comprising: 60 seconds of stimulation plus the computation of one metric (Fig. 4.1); this pattern was repeated until all the metrics were acquired and the condition unfolding was stopped.

At this point, the participant was allowed to take off the headset and rest for some minutes. Whenever he felt ready, the following condition commenced.

This whole scheme was repeated until all the conditions were completed; it took approximately 3 hours in total.

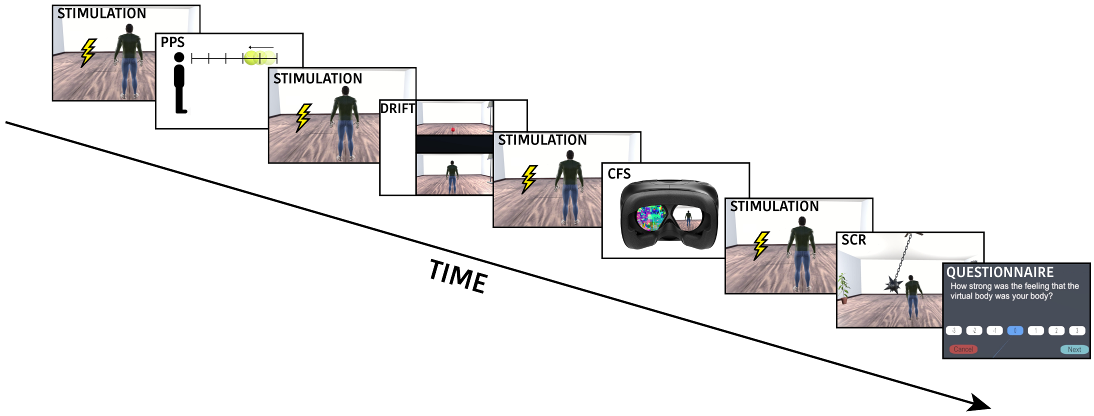

Figure 4.1: ***Schematic representation of the events sequence in a single condition.***
In this example condition 60 seconds of stimulation are alternated with a measure acquisition, following this order: PPS, Drift, CFS, SCR and questionnaires

For each individual, both the order in which different conditions were taken and the one in which various measures were computed inside a single session were randomly changed. This was done in order not to introduce any kind of bias in the results, coming from an habituation effect of the participant.

Before going to the conditions and metrics explanation, the difference between taking the experiment without or with movement is remarked: in the former option, during the TENS stimulation step, the subject was just standing still and no activity was required, in the latter one, instead, he was accomplishing a motor task.

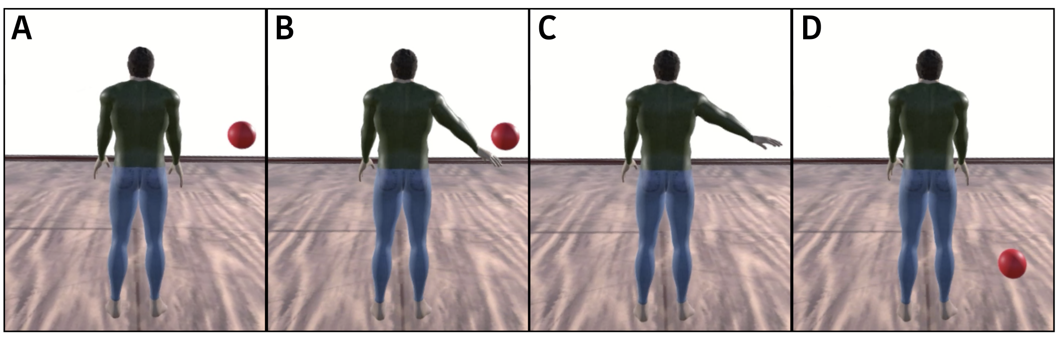

Figure 4.2: ***Schematic explanation of the movement task.***
The subject notices a red ball close to the avatar's right limb (A) and, by raising his own right arm, lifts the virtual one (B) until reaching the ball. Once it has been touched (C), it disappears and a new one pops up in a different location (D).

During this latter phase, some colored balls appeared close to the avatar's hands or feet and the participant, controlling their movements with his own limbs, was required to touch them. As soon as the contact between a virtual limb and a ball happened, this disappeared and another one materialized in a different location (order of balls' appearance was random). A schematic explanation of this assignment is reported below (Fig. 4.2).

The purpose of this exercise was to be sure that the individual was moving during the experiment and, as a consequence, could notice that his actions were reproduced by the avatar. In fact, the potential risk in this case was that the subject would not have moved while undergoing the test, resulting in no difference between movement on and off groups.

4.1 Conditions Description

The possible conditions are listed below dividing between control and experimental ones: the former indicate situations in which electrical stimulation was not present and are treated as a comparison baseline; the latter, instead, are the ones involving TENS and so aiming to demonstrate the hypothesis of the project about the possibility of inducing a body illusion using an electrical stimulation.

4.1.1 Control Conditions

Three control conditions were implemented in the presented protocol and are hereby listed:

1. Visual Only: this condition had been already introduced before and represented an additional control during which the participant neither received an electrical input nor saw a visual one over the avatar.

   Thus, the subject does not receive a tactile stimulation and finds himself in a room staring at an avatar in front of him. As anticipated above in the text Sec. 3.1.2, its aim was to rule out the possibility that only the fact of having a virtual body in the front space could induce a body illusion and to prove consequently the essential presence of multiple stimuli integration.

2. Synchronous classical Full Body Illusion: this represents the reproduction of the traditional experiment.

   Similarly to literature [8, 25, 44], the stick on the real body was moved by the experimenter while, differently from it, the scene the subject was looking at was not a prerecorded video but a VR room with the avatar in the middle and a stick appearing on his back (Fig. 4.3). In this case a synchronous stimulation was delivered, meaning that the perceived touch of the stick was matching in time the one over the avatar.

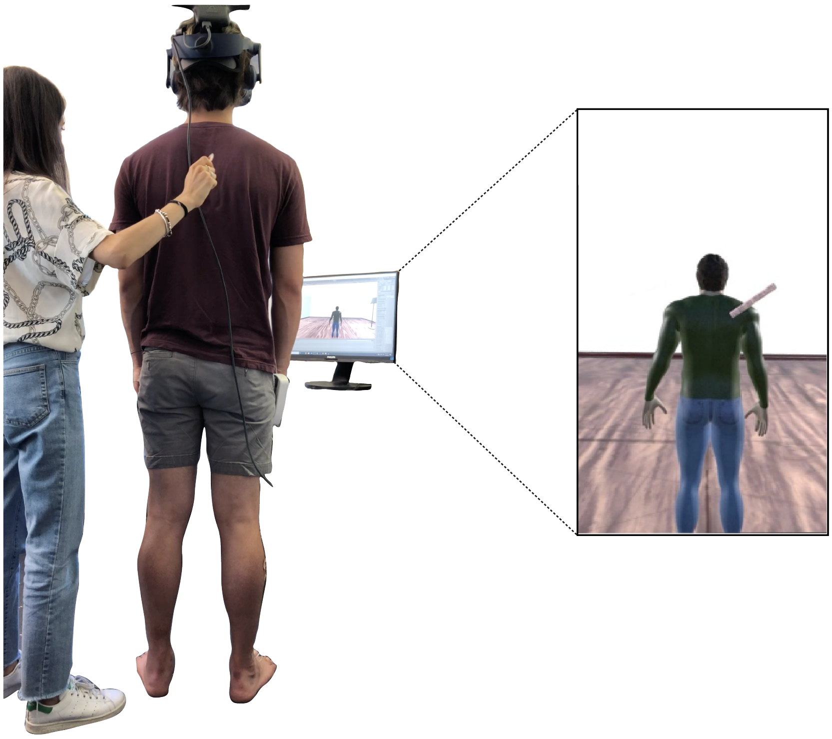

Figure 4.3: ***Classical Full Body Illusion reproduction***.
Representation of a subject undergoing the classical stroking condition: the experimenter was touching his back with a stick while he was looking at the scene, visible on the computer screen which zoom is reported on the right, including an identical stick moving over the avatar.

3. Asynchronous classical Full Body Illusion: this option deals with exactly the same stimulation protocol seen in the previous case, with the only difference that here the moves of the two sticks were not contemporary but opposing, with one going up when the other was heading down.

4.1.2 Experimental Conditions

All the sessions described in the following paragraph include, during the 60 seconds of stimulation, an electrical input delivered to the participant and its visual counterpart (white wavy lines) on the virtual body. What changes between them is the number of involved limbs and their being or not corresponding in time.
A list of all these conditions is below reported:

1. One limb synchronous: the current was delivered only to one foot (the right one) and it was synchronized with the appearance of the white lines on the avatar's right foot;

2. Four limbs synchronous: the activation interested all the four limbs and visual and tactile perceptions were time-matching;

3. One limb asynchronous: the two stimuli were dispensed only to the right foot and the tactile one was delayed with respect to the visual;

4. Four limbs asynchronous: all the four channels were triggered and, same as before, an incongruence was present between the two stimuli timing.

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A summary of all the conditions is below reported (Fig. 4.4).

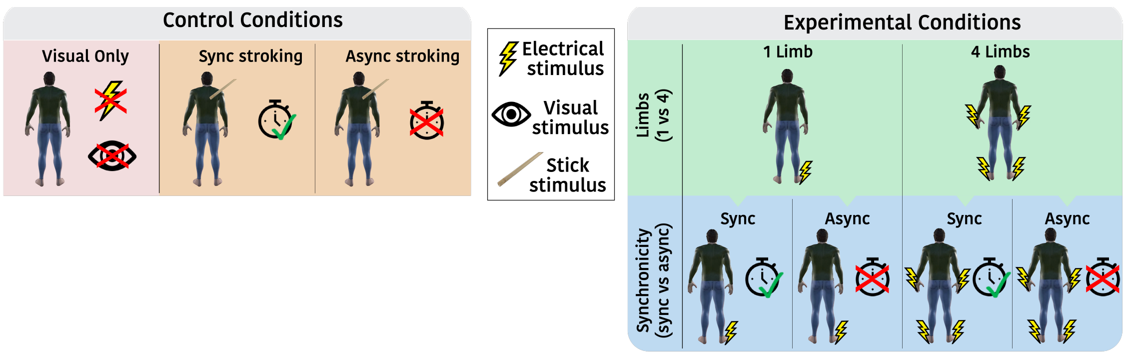


Figure 4.4: ***Schematic list of all possible conditions***.
In the left table the control conditions are listed: the first one is the visual only where no electrical and visual stimuli are present; then the second and third one are the two classical Full Body Illusions, where time matching is present (synchronous) or absent (asynchronous), respectively. In the right table the experimental conditions are listed: the first and third ones are relative to the 1 limb stimulation, with and without time matching, respectively; the second and fourth ones are relative to the 4 limbs stimulation, with and without time matching, respectively.

4.2 Measures description

A detailed outline of all the metrics considered during the experiment, including a description of the method they were acquired with, is reported hereafter.

4.2.1 Quantitative measures

This first paragraph focuses on the objective measurements.

Peri-Personal Space (PPS)

This concept is defined as “the space immediately surrounding our bodies” [33]. It represents the space that can be reached with hands or using a tool and thus it is where human-environment interactions take place.
It is important to bring to mind that whenever a subject perceives something, not a single information is received but many different stimuli are summed together in a process called multisensory integration. This phenomenon had been demonstrated to occur not in the whole external space surrounding an individual but just in a limited one which is, precisely, the Peri-Personal Space [40]. Multisensory integration is a phenomenon saying that the response to a stimulus (e.g. tactile) is faster when a second input of different a nature (e.g. visual) is present [38]; for example, when asked to react to a touch feeling, one is faster in case another stimulus is contemporary present. To better understand this notion, it can be stated that a subject pays attention to all the stimuli inside his PPS, while ignores the ones outside; for example, a knife inside one's PPS can generate fear reactions while the same situation is almost ignored in case it occurs outside this region.
The size of this area was considered in the current project because it had been demonstrated to be related with the occurring of a body illusion [17, 28]. In fact, from literature it is known that whenever an individual experiences an embodiment feeling, his PPS shifts towards the virtual avatar in front of him [28], indicating a self-projection in the front space. Thus, PPS location could give a hint about the occurring or not of a FBI.

Furthermore, subsequent studies proved that not only one PPS exists but, other than a whole-body PPS that can be imagined as the peri-trunk one, also peri-head and peri-limbs PPS can be defined [39]. In this project, both peri-trunk and peri-foot PPS were measured: the former in case of a four-limbs stimulation, the latter a one-foot one.

Considering that Peri-Personal Space is the region where multiple signals are summed together, its computation required to administer stimuli in the space surrounding an individual and observe his responses. Similarly to literature [40], here as well touch and visual stimuli were used: the former consisted of electrical impulses (lasting 100 ms) delivered to the subject; the latter of a tennis ball looming towards him.
The subject was asked to press a button as soon as he was feeling the current pulse, while looking at the ball looming. The electrical input could be given when the ball was at a different distance from the subject: 6 possible gaps were selected and the Reaction Time (RT) of the participant was measured in all cases.
A scheme is represented below (Fig. 4.5): the space length between the standing person and the ball starting point was divided in 6 slots and the impulse could be given at any of these 6 distances (from D1 to D6, with D6 being the closer and D1 the farthest).

In addition to these experimental measurements, also baseline and catch trials were driven: in the former ones, the participant had to react to pulses (located either at D1 or D6) without the ball presence; in the latter (opposite case), he was supposed not to press the button because the ball was approaching but no current was delivered.
The goal of baseline trials was to have the pure subject rapidity without any integration occurring, while the aim of catch ones was to test his attention level.
This acquisition was repeated many times so that more than one RT was available for each alternative; more specifically, each experimental distance (6 in total, from D1 to D6) and each baseline distance (D1 and D6) were tested 10 times and the same for catch trials; the final amount of repetition was 90 (60 experimental, 20 baseline, 10 catch).

From previous studies [38] it was expected that, because of multisensory integration, the reaction to the tactile stimulus would have been faster when it was summed with a

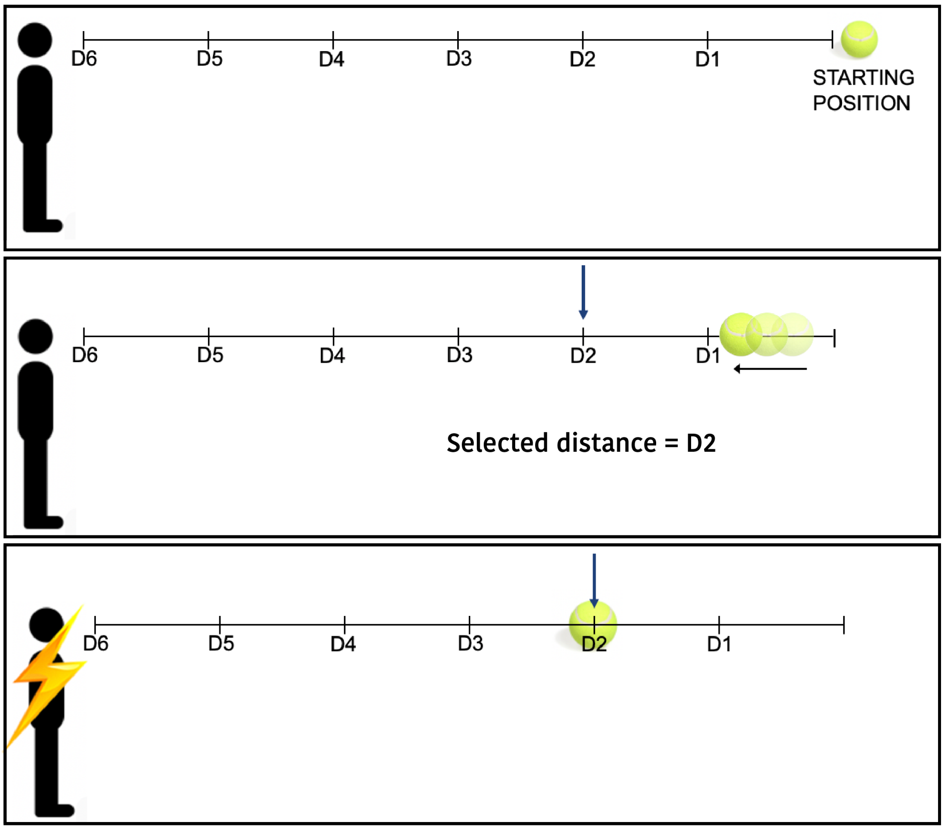


Figure 4.5: ***Schematic representation of PPS implementation*.**
Example of one PPS measure acquisition: the space separating the subject and the ball is divided in 6 equally-sized slots. In this case the distance D2 is selected as the one where the electrical impulse is to be provided, meaning that: the ball starts its trajectory towards the participant and, when it is in D2, the electrical stimulus (represented by the thunderbolt) is delivered to him; he is supposed to react to it with the controller.

visual one. Thus, by comparing experimental RTs with baseline RTs, it was possible to find the right distance at which the presence of the ball (visual cue) made the subject's reaction faster and so, the distance at which stimuli integration was occurring.
Taking an additional step, this position could be assumed as proxy of the PPS boundary [28], bringing to mind the PPS definition as "the space where multisensory integration occurs" [33]. To sum up, each time PPS metric was gathered, RTs to the various experimental, baseline and catch trials were collected and the distance at which the subject became significantly faster with respect to baseline was taken as PPS boundary. Then, by comparing the various conditions' PPS sizes, it was possible to check whether its dimension was correlated with the occurring of a body illusion, as noticed in literature [17, 28].

As discussed above, both peri-trunk and peri-foot PPS were taken into account. The functioning principle was the same in both cases, the only change was the location of the two stimuli: in the first option, the ball moved towards the subject's face and the electrical input was supplied to the right hand (approached to the trunk, pretending the stimulus was there, as expected from literature [39]); in the second one, instead, the ball addressed the right foot and the current was received on the same limb.

Skin Conductance Response (SCR)

This is marked as a physiological metric because it represents the electrodermal response to internal or external stimuli; in particular, it is the skin conductance trend in relation to what a subject is experiencing [43]. In fact, it had been proved that whenever arousing stimuli occur, skin becomes a better electricity conductor, with an increase of its conductance level; for example, when someone is scared, a higher SCR is noticed.

In the following protocol this value was acquired in relation to threatening events referred to the avatar (such as objects suddenly hitting him). The underlying concept, demonstrated in literature papers [11, 32, 1], was that the more the participant was scared by these events (and so the more his SCR increased), the stronger was the identification with the avatar.
Three possible threatening events were implemented:

1. a black spiked ball suddenly appearing and swinging in front of the avatar. This object was designed with `Blender` program and then imported in `Unity`, because the former enables a more detailed definition. It was hung to the ceiling with a chain and both objects were oversized and moved fast in order to look more frightening;

2. the ceiling fan, always present in the room, all at once lowering until hitting the avatar's head. Its movement was managed via a script, imposing its vertical

translation with a high speed; furthermore, also a sway of the avatar's head was added, as soon as it was touched by this object;

3. the crash of the floor below the virtual character, causing its consequent straight down falling. In fact, the room floor, even if not evident, was divided in two parts: one underneath the real subject location and the other underneath the virtual one. During this threat event, the latter was destroyed in many parts with both the avatar and the objects (plant and lamp) falling down. The real subject was allowed in this case to move some steps ahead and look down in the pit.

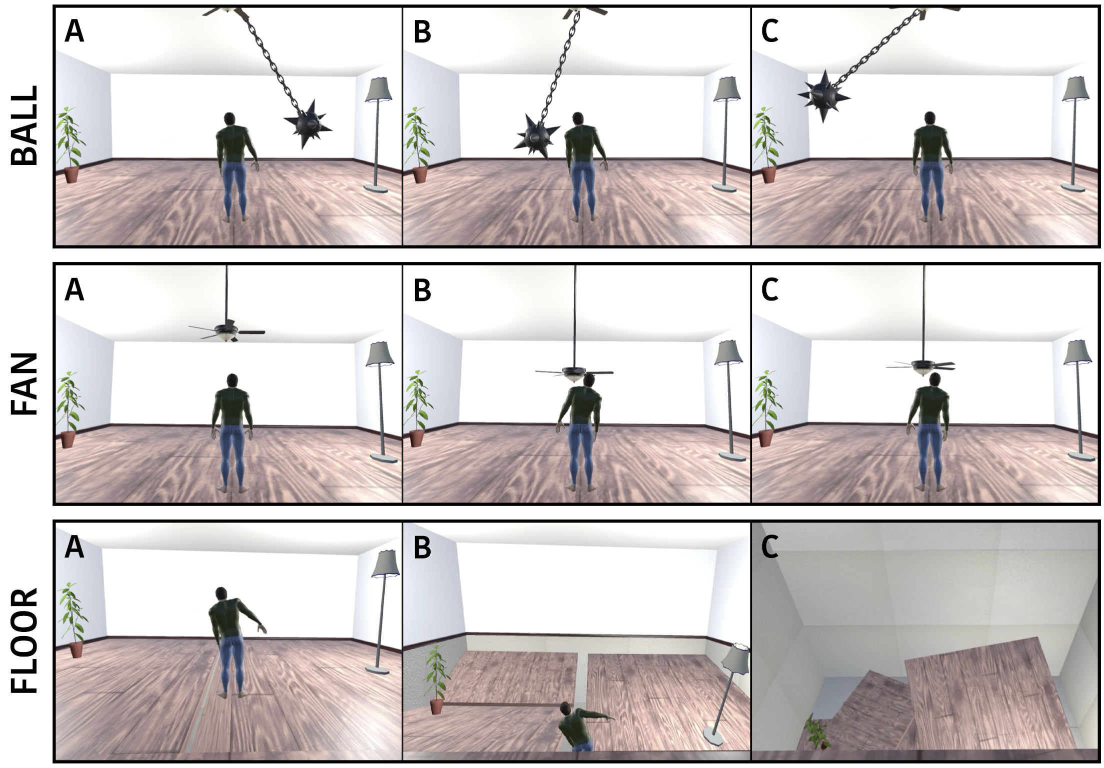


Figure 4.6: *Representation of the three implemented threats.*
The first line is relative to spiked ball threat, where the ball swings from right to left. In the second one, the fan threat is reported with the object going down and hitting the avatar. In the last one, the falling floor event is displayed, including the pit view in panel C.

This conductance value was collected only in the 4 conditions including TENS in order to limit the number of SCR acquisitions; in fact, from previous studies, it was known that this metric could cause habituation and anticipation if repeated too many times [23], with the risk of obtaining biased results.

For every computation, one out of the three possible scary stimuli could be selected. Practically speaking, this quantity was calculated using *eSense Skin Response* device provided by Mindfield which comprises two electrodes, placed to the subject left hand (Fig. 4.7), similarly to literature [12, 22, 23, 32],connected via cable to a smartphone for data saving through the eSense App.

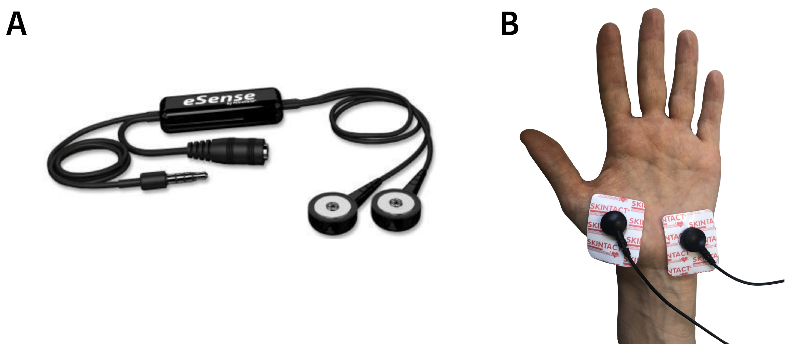


Figure 4.7: ***SCR hardware***.
SCR recording device (A) with a jack extremity to be inserted in the smartphone and the other bifurcating extremity where the electrodes are attached. They are then located on the participant's left hand, as shown in the figure on the right (B).

The recording was characterized by a sampling rate of 5Hz and lasted for a whole condition; then, during later data processing, only data belonging to the relevant time intervals were taken into account. In particular, knowing the right instant in which the frightening event appeared (given as output from a script), data of the 6 seconds preceding and following it were kept. This was done because final SCR was calculated as the difference between the mean value of the 6 seconds following the stressful event and the 6 ones preceding it [12].
Considering $\bar{t}$ as the time instant of the threat event, SCR index was computed in this way:

$$SCR_{index} = \frac{\sum_{i=\bar{t}}^{\bar{t}+6} SCR_i}{6} - \frac{\sum_{i=\bar{t}-6}^{\bar{t}} SCR_i}{6} \tag{4.1}$$

Self-localization Drift

This measure is relative to the "perceived self-location", indicating the position in space where the subject localizes himself.

The basic concept is that when the subject is able to correctly identify his position in the external environment, it means he has a high awareness of his body; conversely, in case a body illusion is occurring, the subject localizes himself closer to the virtual character [23, 25, 27]. This mis-localization towards the avatar is known as "proprioceptive drift" and the same phenomenon was observed related to the hand localization in the RHI [4].

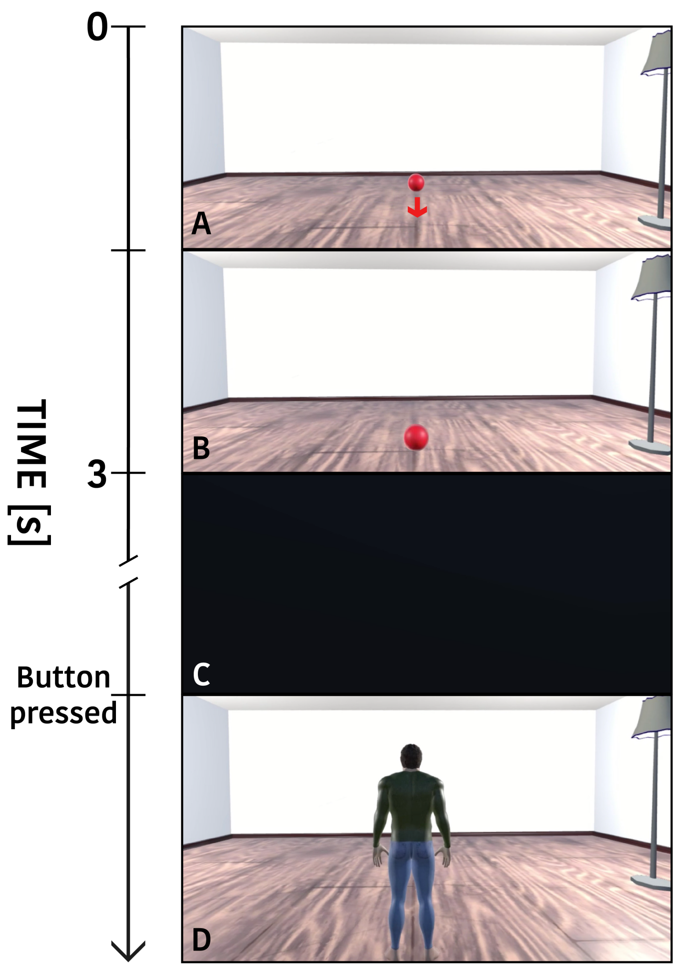


Figure 4.8: ***Schematic representation of Drift measure acquisition***.
At the beginning (A) the avatar vanishes from the room and a red ball appears on the floor, approaching towards the subject (A, B). After 3 seconds, the screen becomes black (C) so that the subject does not have any visual cue anymore. At this point he is required to press the button on the controller when he thinks that the ball reaches his feet; as soon as the button is pressed, the avatar shows up again (D) and the measure is concluded.

In literature [23, 25], its computation required to displace the subject (once completed the 60 seconds stimulation) and ask him to return to his initial position: the difference between where he was self-localizing and the real position was taken as proprioceptive drift, indicating how strong the embodiment was. As said before (Sec. 2.2), this pro-

tocol was defined as not completely clear and reliable and so, a different one was here employed, introduced by a recent study [27]. The main difference was that, in this case, the subject was not required to move, earlier identified as principal limit of the previous technique (Sec. 2.2), thus enabling to better maintain the illusory self-location.
The functioning of this novel drift method is explained as follows. First of all, the avatar was removed from the scene so that the subject found himself in an empty room; then, a red ball appeared on the floor some meters ahead and started rolling towards the participant with constant velocity. After 3 seconds, the screen became black and the subject (who had not any visual cue anymore) was required to press a button on the controller (held in his hand) when he imagined the ball passed in between his feet (Fig. 4.8).
In this way it was possible to understand more precisely where the individual localized himself in space, because his perceived position corresponded to the ball location when the button was pressed. Moreover, this technique allowed to just focus on the anterior-posterior axis, because ball was moving only along this axis.

Continuous Flash Suppression (CFS)

This measure consists in a novel metric able to assess the level of conscious awareness that an individual demonstrates towards an object of interest [36, 48] (in this case represented by the avatar). Its functioning is based on showing some colored squares, called Mondrian masks (Fig. 4.9), flashing at 100 Hz, to the participant's dominant eye, with the aim of suppressing the scene he is looking at from awareness. In fact, what happens is that the squares catch one's attention at the beginning, making the scene visible only after a while [36, 48].
In the current implementation, Mondrian masks were created using `CFS Matlab Toolbox` [29] which enables to obtain either differently or equally-sized squares and also greyscale or colored ones; colored squares with different dimensions were selected in this case.
During metric acquisitions, these images appeared on the right lens of the VR headset while the other one continued to focus on the virtual room with the avatar (Fig. 4.9): the result was that the subject's left eye was exposed to the virtual environment while

the right one was masked with the colored squares. This process continued for 60 seconds, time interval during which the participant was required to keep the button on the controller pressed as long as he was seeing the virtual body, but to release it as soon as it disappeared, with the squares dominating his whole field of view.

During successive data processing, the percentage of time (over 60 seconds) during which the avatar was visible (called dominance time) was extracted and taken as index of the individual awareness towards the virtual character.

The conclusion that could be driven was that the higher the avatar dominance time (indicating that the avatar was visible for the major part of time), the more significant this figure was for the subject and more likely a FBI was occurring. Said with other words, a higher dominance time is correlated to an increased level of ownership [48], because whenever an identification with an avatar occurs, it becomes a more relevant visual stimulus for a subject, who becomes highly aware of it.

In literature, this measure had been previously implemented presenting 2D images on a screen, but then also validated in virtual reality [24], enabling to make use of it in the current protocol.

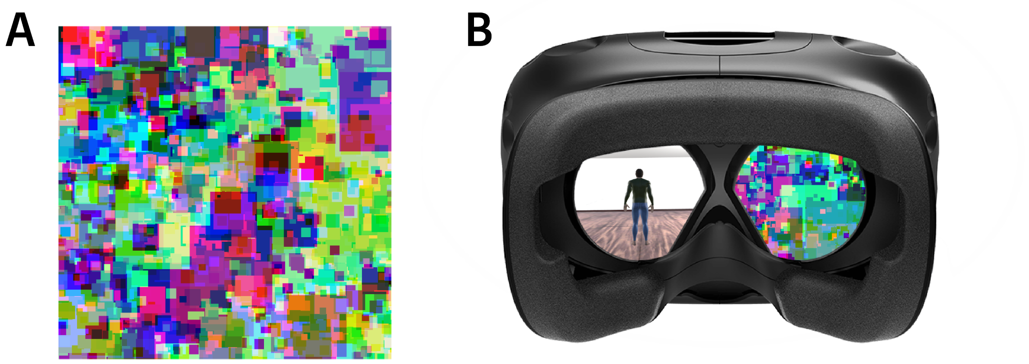


Figure 4.9: ***CFS metric explanation***.
Firstly (A) an example of a Mondrian Mask is reported and then (B) the vision of the subject during CFS measurement acquisition is illustrated. The VR headset is here reported with 2 different images on its lenses: the right one (and so the right eye of the subject) is staring at the flashing Mondrian masks, while the left one (and so the left eye of the subject) is still looking at the virtual room with the avatar inside.

4.2.2 Qualitative measures

In this section a complete description of the subjective measurements is presented.

Embodiment questionnaire

This involves a total of 11 statements, comprising both experimental and control ones; these latter were weird sentences, such as "It seemed as if I might have more than one body" (Appendix A, Q3), expected to be low-rated, which aim was to control that the subject was not giving random answers. All items regarded different concepts and were divided as follows:

1. Feeling of ownership towards the avatar (Q1, Q2) and the relative control (Q3);
2. Touch sensation experienced and whether it seemed produced by the visual stimulus over the avatar (Q4, Q5);
3. Self-localization with respect to the avatar (Q6, Q7) and the relative control (Q8);
4. Agency towards the virtual body, indicating the ability to command it (Q9, Q10) and its control (Q11).

All these questions were extracted from literature [12, 13] and were to be rated on a scale from -3 to +3, with the former indicating a total disagreement with the sentence and the latter a complete agreement.
Additionally, two questions regarding vividness and prevalence of the experienced body illusion were included: the first was relative to the strength of the illusion and was rated on a scale from 0 to 10, the second, instead, regarded its duration and was denoted with a percentage value (thus varying from 0 to 100).

The overall form, counting in total 13 items, was submitted to the participant at the end of each condition, allowing him to sit down but not to remove the headset as it was implemented in the VR environment. Specifically, a panel appeared on the VR screen (Fig. 4.10), reporting the question and 7 interactive buttons (containing rates from -3 to +3): the subject could scroll over them using a laser pointer coming out from the controller and select his answer by pressing the button on the back of the same controller. Once done, he was supposed to press the "Next" button to go to the following question or, otherwise, to select "Cancel" in order to change the provided answer.

This process was continued until the whole questions set was accomplished.

A complete list of the questions is reported in Appendix A.

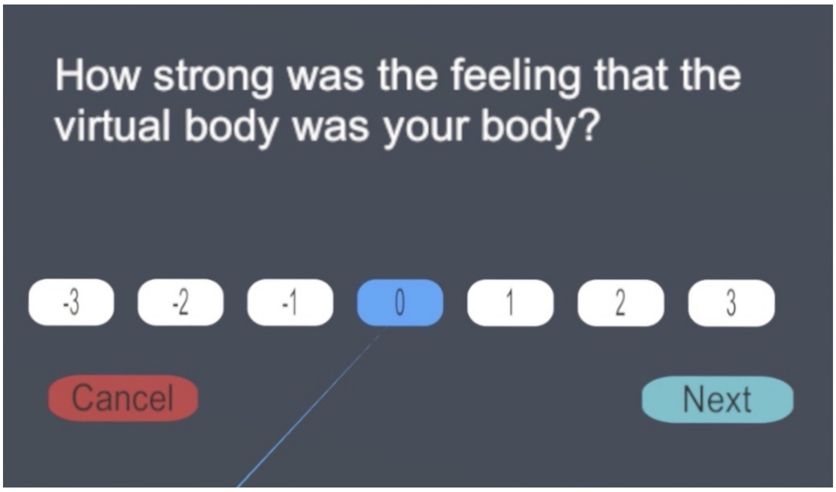


Figure 4.10: ***Questionnaire panel in Virtual Reality***.
Example of a questionnaire panel shown in VR. In the upper part there is the text of the question, in the one below, instead, the buttons to answer. Using the blue laser coming out from the controller, the participant selects the desired one. In addition there are also the "Next" button to pass to the following question and the "Cancel" one to change the provided response.

Phenomenology of Consciousness Inventory (PCI) questionnaire

This constitutes a second questions set, comprising 6 items, presented after the previous one, using exactly the same VR implementation but touching on different arguments. These questions were retrieved from Phenomenology of Consciousness Inventory [31] questionnaire found in literature, which is a form dealing with various sub-sections relative to the personal perception of the own body, feelings and thoughts in reference to a preceding stimulus circumstance.

In particular, "Body Image" and "Self-Awareness" sub-sections were here taken into account, in order to evaluate whether the subject was completely conscious of his external body during the experiment or he was identifying with the virtual avatar instead. The first section deals with the concept of separation between the own body and the world, assessing whether the subject was able or not to clearly distinguish his body from the external environment; the second one, instead, focuses on the awareness that the individual demonstrated towards himself.

The presented items are couples of sentences separated from a seven-point scale (between 0 and 6): 0 is to be selected in case of total agreement with the left-side statement, 6 in the opposite case of total accordance with the right-side one. Also in this form the buttons “Next” and “Cancel” were present.
A complete list of the questions is reported in Appendix B: items Q1, Q2 and Q3 belong to the Body Image subsection, while Q4, Q5 and Q6 to the Self-Awareness one.

In addition to these forms acquired during the experiment running, another one, the Body Awareness Questionnaire (BAQ) [41], was submitted to all subjects some days after taking the experiment.
This is an 18-items scale designed to assess subject’s attentiveness to normal body processes (i.e., interoception), such as the sensitivity to body cycles and rhythms, the ability to detect changes in normal functioning and to anticipate bodily reactions. All the 18 questions were answered on a scale from 1 to 7 and the final mean rating furnished a proxy of how aware a subject was, in general, of his internal feelings. A complete list of the questions is reported in Appendix C.
This step was taken because in case someone had reported a low awareness level, meaning that he was less likely to undergo a body illusion, he should have been excluded from this kind of experiments; in fact, responses to this form were used as exclusion criteria preceding final data analysis. This decision was reinforced by the fact that individuals with a low score also demonstrated inconsistent results in other metrics; thus, a suggest for future experiments would be to take this form during subjects’ recruitment, in order to directly exclude them in case of a low score, without even taking the experiment.

A representation of the different tested conditions and metrics is offered in the video reported in the Additional Infromation section (Appendix D.2.7).

4.3 Statistical Analysis

Hereafter a description of the performed statistical analysis is reported, with the support of code fragments where needed.

Statistical analysis was conducted using `Matlab2019`, following the same method for the three considered metrics: questionnaires, PPS and self-localization drift.
The aim of this step was to check whether, with respect to one metric, there was an effect of condition, and so whether data gathered from different conditions came from the same distribution or not. Practically speaking, in case 2 alternatives were compared, 2 arrays (where each data point belonged to a participant) were tested and the resulting p-Value told whether they were significant different ($p < 0.05$) or not ($p > 0.05$).
First of all the normality of data was controlled using the one-sample Kolmogorov-Smirnov test on the data vectors involved in the analysis. An example is here reported with *C1* and *C2* indicating 2 generic conditions:

```
H1 = kstest(EmbQuest_C1); % Embodiment answers vector for C1
H2 = kstest(EmbQuest_C2); % Embodiment answers vector for C2
```

The Matlab function kstest() returns a value *H*, which is the test decision for the null hypothesis that the data in the input vector come from a standard normal distribution, against the alternative that they do not come from such a distribution; it is 1 if the test rejects the null hypothesis at the 5% significance level, 0 otherwise. In the current example *H1* and *H2* are the two values relative to the embodiment answers vector in the first (`EmbQuest_C1`) and second condition (`EmbQuest_C2`).
The major part of time data points were not normal-distributed and for this reason non-parametric statistical tests were used in the following analysis,.
In case of a double-fold comparison, the Wilcoxon signed rank test was performed between the 2 conditions in this way:

```
pValue = signrank(EmbQuest_C1, EmbQuest_C2);
```

This code line returned the p-value of a paired, two-sided test for the null hypothesis that the 2 vectors came from a distribution with zero median at the 5% significance level. In case $p < 0.05$, the 2 conditions were assumed as significantly different for the particular metric, otherwise only trends could be retrieved from data but no firm statements.

In case of a three-fold comparison, instead, the Kruskal-Wallis test was used, which is similar to the previous one but allows to compare more than two vectors at a time:

```
[pValue, Table, Stats] = kruskalwallis([EmbQuest_C1
    EmbQuest_C2 EmbQuest_C3], ['C1'; 'C2'; 'C3'], 'off');

figure()
Comparison = multcompare(Stats);
% Stats taken from kruskalwallis' outputs (line 1)
```

It returned the p-value for the null hypothesis that the data in each column of the matrix (put as first function input) came from the same distribution, using the Kruskal-Wallis test. The alternative hypothesis was that not all samples came from the same distribution.

The first input was, as before anticipated, the matrix containing all the conditions data-vectors as columns (data from a specific metric); the second was a vector with the conditions' names; the last just indicated not to display the resulting ANOVA table and box plots.

In this example, the final p-Value is relative to the multiple comparison, so, in order to get the matrix of the pairwise comparison, the `multcompare()` function is used (as reported above), which exploits the information contained in the `stats` structure obtained from the `kruskalwallis()` function. It also displays a graph where each group is represented with an horizontal line: if two lines are disjoint, the corresponding groups are assumed as significantly different, the opposite, instead, in case lines overlap.

4.4 Experimental design

As mentioned above, three variables were investigated in the current project, specifically: synchronicity (either synchronous or asynchronous), number of stimulated limbs (either one or four) and movement (either on or off, indicating whether the tracking was active or not). The various combinations of these factors generated experimental conditions, to which control ones were added (explained above, Sec. 4.1).

Considering the overall design, the experiment followed a mixed factorial design for the three manipulated factors: movement was a between-subject variable while TENS synchronicity and number of limbs were within-subject variables. This meant that not all the subjects took both movement options but the total sample size was divided in 2 distinct groups:

- "Movement OFF" group: taking the experiment standing still, without movement tracking;
- "Movement ON" group: experiencing a congruent visuo-motor condition where movement tracking was active and so personal actions where real-time reproduced by the virtual body.

This was done because in a previous work [6] a limitation of the within-subject design for the movement variable had been observed, caused by a ceiling effect of this latter. It indicated that movement was able to produce a stronger FBI with respect to the other ones; in fact, a higher embodiment feeling was registered when movement reproduction was available [6], as could have been expected, and this was hiding the outcomes of other parameters (synchronicity and number of limbs), overwhelming them in the body illusion induction.
Instead, admitting just one movement option per participant, allowed to better discriminate the results coming from the other two factors. These latter, on the contrary, were planned as within-subject components, taking into account that in this way a limited number of participants was required with respect to a potential alternative where all the three aspects were considered as between-subject.
The practical consequence of this decision was that all individuals experienced both the one and four limbs TENS stimulation; the synchronicity effect, instead, was evaluated only for the subjects in the movement-off group but not for those in the movement-on one. This was justified saying that, in order to evaluate the outcome of synchronicity, it was considered enough to just test the movement-off group in the synchronous vs asynchronous TENS circumstances; thus, it was not necessary to repeat the same

comparison for the movement-on one. The big advantage was a reduction of the experimental duration (considering that this group also needed trackers placement on the subject, which required additional time). The total experiment duration was about 4 hours for the movement-off class and 3.5 hours for the movement-on one.

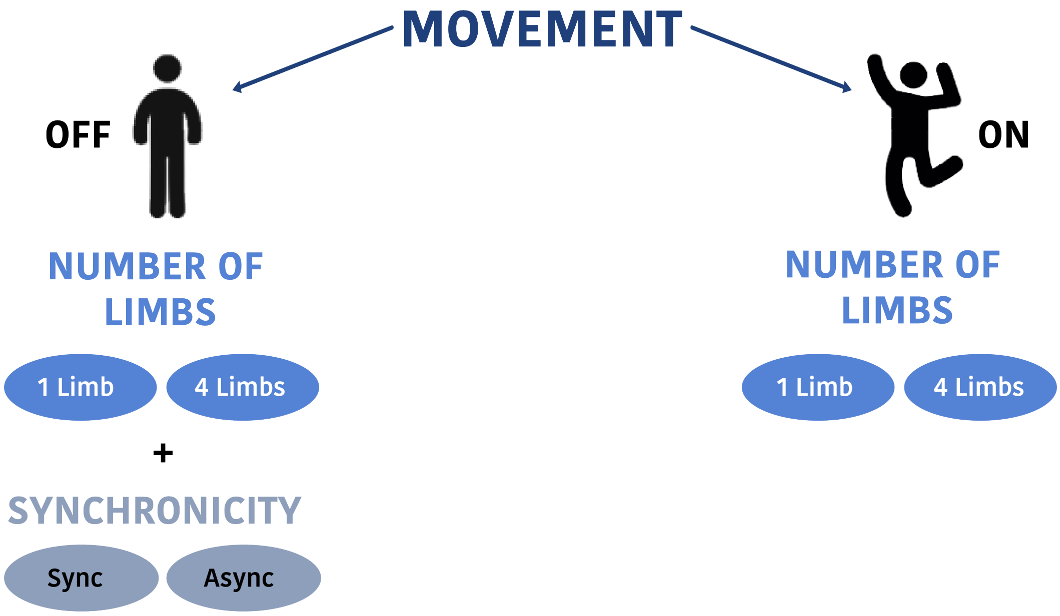


Figure 4.11: ***Schematic representation of the followed experimental design.*** *Movement is the between-subject variable that divides the total sample size in 2 groups. Number of limbs is considered in both groups, with all subjects taking both options (one/four limbs); synchronicity is considered only in the movement-off batch, with subjects taking both alternatives (synchronous/asynchronous).*

A schematic representation of the final experimental design is reported above (Fig. 4.11) to better understand conditions allocation.

For the movement-off group, experimental conditions were: synchronous TENS to 1 Limb, asynchronous TENS to 1 Limb, synchronous TENS to 4 Limbs and asynchronous TENS to 4 Limbs; for the movement-on one, instead: synchronous TENS to 1 Limb and synchronous TENS to 4 Limbs.

In addition to the listed alternatives, all subjects underwent the three control conditions (visual only, synchronous classical stroking and asynchronous classical stroking). The 2 latter ones were identical for both on and off batches, as movement was anyway not included in the classical stroking; the only difference was in the visual only: during the 60 seconds of no stimulation, in the "off" option the subject was required not to do anything, while in the "on" one he was supposed to take the movement task, touching the balls around him.

The total number of tested subjects was 27 (16 males, 11 females).
With subsequent data analysis, 2 of them were excluded based on the Body Awareness Questionnaire (BAQ) [41] results. As anticipated before, in fact, the mean rating retrieved from this form was used as exclusion criteria because a small score, indicating a low awareness of a subject towards his internal feelings, suggested that he was not likely to experience an embodiment illusion and so that he should not have been considered in the following data analysis. In particular, the average of the 18 items was considered as indicator of the level of awareness and compared with the average coming from all subjects. Those with a BAQ index of 1 SD below the overall mean were excluded; in the whole participants set, 2 met this constraint and were thus removed from subsequent evaluations. This conclusion was supported by the analysis of other measures as well; in fact, individuals with a low score also demonstrated inconsistent results in other metrics, confirming that it was correct to exclude them. It suggests that in future studies this form should be taken during subjects' recruitment, in order to directly ignore them in case of a low score, without even taking the experiment.
Hence, the final sample size was 25, with 11 individuals in the movement-off group and 14 in the movement-on one; they were included in the whole set of analysis and considerations leading to conclusions driving.

Chapter 5

Experiment Procedure

In this section a complete description of all the steps taken during a running of this experiment is outlined.

First of all, it is possible to distinguish between two main phases: the former is called calibration, during which current amplitude and pulsewidth are defined and the participant subjectively reports the felt sensations; the latter consists in the real experiment, with the subject undergoing the different test sessions including stimulation and measures acquisition.

5.1 Calibration

The aim of this starting phase was to find the correct amplitude and pulsewidth values of the current used during the test; these were specific for each limb and participant as they change across nerve type and subject, respectively.

First of all, it required to connect Rehamove device to the PC and open a Graphic User Interface able to command it: the correct device name and COM port needed to be selected and then it was possible, opening the Stimulation Settings window (Fig. 5.1), to deliver a current with a varying parameter (selected between frequency, pulsewidth and amplitude).

The process started by stimulating one limb (for example the left foot) with amplitude as varying parameter (linearly increasing) while frequency (always kept at 50 Hz) and

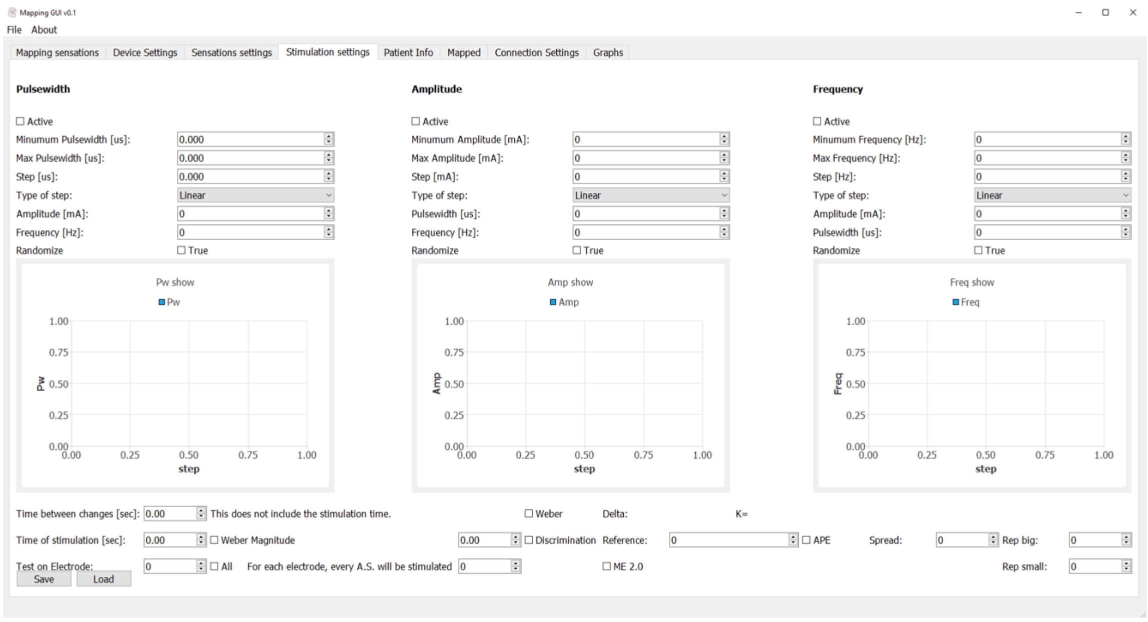
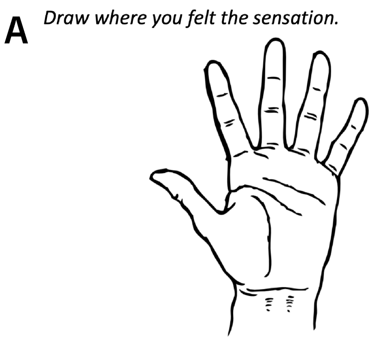


Figure 5.1: *Graphic User Interface used for calibration*.
Screen of the "Stimulation Settings" window in the Graphic User Interface used for the calibration phase.

Pulsewidth (150 Hz) were constant. The subject was asked to tell at which intensity the feeling became somatotopic as this was the sought-after peculiarity of TENS stimulation. However, somatotopy is strictly related to the electrodes positioning because it requires to correctly target the nerve so that the sensation can spread through its branches. Thus, it could happen that the subject was feeling an increasing current but just under the electrodes; in such eventuality, their position was changed, and the process repeated.

Once the right electrodes location and current amplitude level were found, the second calibration step began, regarding the identification of minimum and maximum pulsewidth. The final stimulation, in fact, was varying in a range defined by these latter values, following a Gaussian shape as explained before in the text (Sec. 3.2.2). During this initial phase, frequency and amplitude values were constant (the former set to the amount previously found) while pulsewidth was increased following a ramp trend. In this case, the participant was asked to inform the experimenter when he was experiencing a somatotopic sensation of intensity 2 (on a scale from 0 to 10), indicating a light feeling; at this point, Rehamove was stopped and he was required to fill a form regarding the location and type of the perception.

Responses were given using an i-Pad where he had to color the area (over a foot or hand painting) where he felt something and rate (on a scale from 0 to 10) the kind of sensation, choosing from a list of different feelings: pressure, pulsation, electricity, tingling, twitch, warm, cold, pain and the in-loco one (indicating the intensity perceived directly below the electrode). The screens of the two sections of this form are reported below (Fig. 5.2).
Completed the questionnaire, Rehamove was re-activated and the stimulation continued (starting from the value it had been stopped at) and the individual was asked to warn when he was experiencing a somatotopic sensation of intensity 8; at this point, identical to before, current was stopped and the same form answered.



B *How would you describe the sensation? Circle all that apply.*

Pressure	0	1	2	3	4	5	6	7	8	9	10
Twitch	0	1	2	3	4	5	6	7	8	9	10
Tingling	0	1	2	3	4	5	6	7	8	9	10
Touch	0	1	2	3	4	5	6	7	8	9	10
Warm	0	1	2	3	4	5	6	7	8	9	10
Cold	0	1	2	3	4	5	6	7	8	9	10
Pain	0	1	2	3	4	5	6	7	8	9	10
Electricity	0	1	2	3	4	5	6	7	8	9	10
Pulsation	0	1	2	3	4	5	6	7	8	9	10

How strong was the sensation underneath the electrode?

0 1 2 3 4 5 6 7 8 9 10

Figure 5.2: ***Form for sensation characterization***.
Representation of both form sections: the former (A) where the subject has to color over the limb image (which is a hand in this case but can also be a foot), the latter (B) where he is required to rate the experienced feelings.

This pulsewidth step was repeated 3 times and then the average of the levels rated with 2 was taken as minimum, while for the maximum the one of the levels rated with 8 was taken into account. This whole process was repeated for all the the 4 channels (each one stimulating one limb) with a total duration varying between 45 minutes up to 1 hour.
The detected values were then inserted in Unity 3D and used for the stimulation during the experiment; data collected with the forms, instead, were processed with Matlab and saved into tables.

5.2 Experiment

Once the calibration phase was terminated, the proper experimental steps could begin: the project file was opened in Unity and the participant wore the headset.
In case movement was included in the experiment, also the 3 trackers (1 on the chest and 2 on the feet) were positioned and the person was required to hold the controllers in his hands; otherwise, trackers were not included and only one controller was needed, but just during measures collection.
First of all, after opening the Unity project, the experimenter was supposed to type in the current values just found during calibration as parameters of a code script, called "Session Control", which acted as a master controller during the whole experiment length (Fig. 5.3, A).

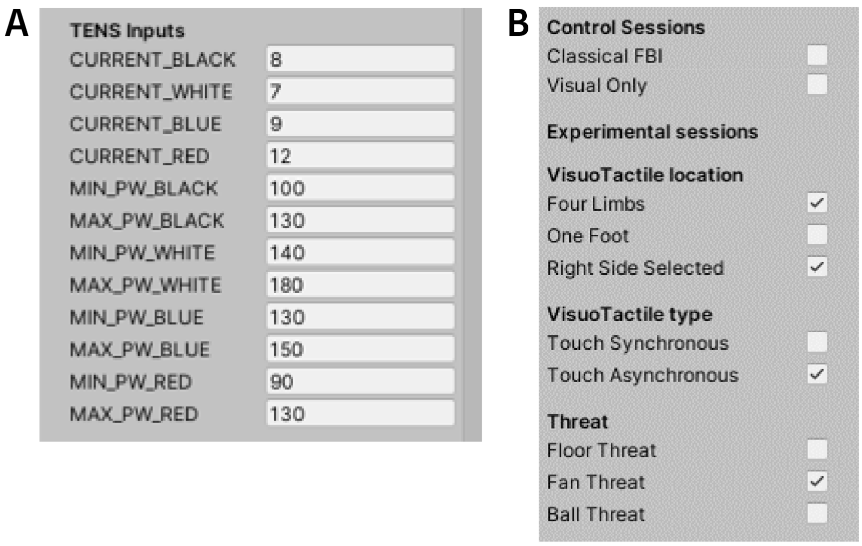


Figure 5.3: ***Code parameters***.
(A) Screen of "Session Control" in Unity Inspector where amplitude and pulsewidth values need to be inserted before starting the experiment. A different color indicates a different channel respectively. (B) Section of the inspector where the condition to run is selected: the experimenter has to select one session among control and experimental ones; in this latter case, both location (either 1 or 4 limbs) and type (either synchronous or asynchronous) need to be specified. Then, one threat between the 3 implemented has to be chosen as well.

5.2.1 Balancing

This step represents an additional check over the inserted current values, before starting with the actual experiment. It was accomplished activating the “Balance” script and pressing “play” on Unity: through a keyboard input, a pulsewidth-modulated stimulation (identical to the one that would have been received during the experiment) started and the subject was required to indicate whether the intensity was evenly distributed among limbs or not and, in this latter case, which channels needed to be modified (specifically it was the amplitude level the parameter either increased or decreased). At this point the current was stopped and requested changes applied; then, the same was repeated.

When a balanced perception was reached, the run was interrupted. At this point, the real tests and measures could take place.

This balancing step was taken in the Unity environment and not during calibration because the Graphic User Interface used to command the stimulator allowed to activate just one channel at a time while during this step all 4 were working. The reason is that here the aim was to give the participant an example of what he would have felt during the experiment and so the ”stronger” case, stimulating 4 limbs, was chosen.

5.2.2 Conditions

Once the balancing phase was concluded, the experiment could commence with the first condition; this was set by simply checking a box in the Unity Inspector window relative to the “Session Control” script. A screen of this window is reported above (Fig. 5.3, B): a list of all conditions with a box on their side is present. The experimenter was required to choose one among the control and experimental ones; in the latter case, both the location (either one or four limbs) and the type (either synchronous or asynchronous) needed to be selected as well. The check on “Right Side Selected” just meant that when the stimulation was to one limb, the involved one was the right foot; otherwise, it would have been the left one.

A second decision demanded to the experimenter at this stage was the threat type: one out of the three possible fear stimuli had to be checked.

Both the condition and threat selections were done by the researcher in a random way, meaning that the order was different across subjects.
This "Session Control" script was the only one including parameters that had to be set; once it had been done, the *"Play"* button on Unity could be pressed and the chosen condition (taking approximately 20 minutes) started.
The session run was organized in this way: 1 minute of visuo-tactile stimulation (either TENS or stick, depending on the particular condition) was followed by a metric acquisition; this patterned continued until all measures were taken, with questionnaires being the last one.
Then, once concluded this latter too, the subject was allowed to take a rest while the experimenter was setting the parameters for the following condition.

participants individuals Inside a single condition, also the order in which measures were acquired was chosen by the experimenter randomly, as both among participants and among conditions (for the same individual), the order was different and did not follow a scheme. The selection was done by just pressing a key on the PC keyboard; in fact, each measure was associated to a letter so that whenever it was pressed, the relative metric acquisition started.
Letter assignment was done as follows:

- "p" → 60 seconds stimulation + PPS recording;
- "d" → 60 seconds stimulation + Drift measurement;
- "f" → 60 seconds stimulation + CFS implementation;
- "t" → 60 seconds stimulation + threat event;
- "q" → questionnaire panel appearance.

All these steps were repeated until the total number of scheduled conditions was accomplished and the experiment was over.

Chapter 6

Results and Discussion

The following section is dedicated to the report of the relevant project outcomes, considering whether they support or not the demonstration of the main hypothesis which has been already presented at the beginning of this exposition.
Before going into the details of the post-experimental analysis, other two results are shown: the former about the acquired metrics and their reliability with respect to the protocol, the latter regarding the answers recorded from the participants during the calibration phase.

6.1 Metrics conclusions

This section deals with the remarks made about the implemented measures, which can be considered already a result since they were evaluated with an a posteriori data analysis.
Looking at data gathered from different experimental sessions, it was possible to drive conclusions about their reliability, defining unreliable a measure that does not allow to discriminate between experimental conditions, meaning that, even if the stimulation protocol is changed, no differences arise from data measurements. In this eventuality, when stimuli condition did not impact results from a metric, this latter was marked as

inaccurate for the performed study. A double cause could justify this behavior: either the measure was collected with a wrong implementation, leading to false findings, or it was not related to the basic concept of the project (FBI principles in this case) and so it was not affected by stimuli modifications.
Regardless the origin, whenever a measure was found to be unreliable it was excluded from the a posteriori analysis as, otherwise, inconsistent deductions would have been made. However, talking about future experiment and possible improvements, two different decisions were taken depending on the unreliability cause: in the first case, the measure should not have been removed from the protocol at all but a different implementation was required, in the second one, instead, the metric should have been cancelled, as it could not give any interesting cue regarding the hypothesis demonstration.

The quantities registered in the current design, already introduced before in the text, are here listed: Questionnaires, Peri-Personal Space (PPS), Self-localization drift, Continuous Flash Suppression (CFS) and Skin Conductance Response (SCR).
Questionnaires, PPS and Self-localization drift were assessed as reliable because different trends were retrieved from data, linked with distinct conditions running.
On the contrary, the same remarks were not true anymore considering CFS and SCR, which were thus marked as unreliable. Their results appeared to be completely random, without any tendency that could allow to drive consistent conclusion about the examined body illusion.
To better explain the reliability outcomes, it is useful to consider, among the main experimental comparisons that were conducted (reported below in the text Sec. 6.3), the number of times each metric was both significant and in line with other measures and with literature, giving support to the conclusion driving. This is exactly what the following table displays (Tab. 6.1), reporting in percentage the number of times the specific metric proved to be reliable.

Focusing on Continuous Flash Suppression (CFS), its implementation, retrieved from previous works [36, 48], presumed that the subject was looking at the virtual scene with the non-dominant eye, while the dominant one was excited with some colored flashing

Table 6.1: *Table reporting the reliability value for each metric implemented din the protocol. It is expressed as a percentage of the number of times the measure outcome was significantly in line with both other metrics and what was expected from literature.*

metric	reliability
Questionnaire	100%
Peri-Personal Space	80%
Self-Localization Drift	60%
Dominance Time	20%
Skin Conductance Response	0%

squares [29]. The collected quantity was the *Dominance Time*, which represents the amount of time, in seconds, during which the avatar was visible and predominant over the squares, considering an acquisition period of 60 seconds. From literature it was expected that the more the participant was experiencing a body illusion, the more the virtual body was relevant at his eyes and the higher was the dominance time [48]. However, in the presented experiment, no significant *Dominance Time* differences were found comparing conditions, indicating that no links existed between the running of a condition and this value; the major part of times it was really high, preventing to discover any correlation with the illusion. For this reason, CFS was excluded from further analysis and will not be reported in the result presentation later on in this exposition. Anyhow, considering that an embodiment illusion is connected to the personal perception of the own body with respect to the avatar's one, this consciousness measure should be related with the occurring or not of a Full Body Illusion and so, not discarded at all. The problem encountered in this case was probably due to a wrong technological implementation of this metric; some encountered issues were: participants closing the right eye so not to see the squares anymore or some, instead, to whom it was not completely clear when they had to press the button during the acquisition. Future experiments should try to overcome these shortcomings and both realize a better execution and provide a better task explanation, in order to make CFS reliable.

Going now to the Skin Conductance Response, the conclusion was different. From previous papers [12, 22, 23, 32] it was supposed that the more the subject was embodying the avatar, the more he would have been scared by the threats addressing it and the more his SCR level would increase.

Anyway, this measure was categorized as unreliable, as said before, because no links could be retrieved between the occurring or not of a body illusion (depending from the condition) and this numerical quantity. For this reason, SCR was excluded from further analysis and so, will not be reported in the result presentation.

However, the causes of this behavior and following conclusions were different in this case. Here, the main issues were room temperature and participant's movements: in fact, both variables were known to alter the SCR value but, at the same time, difficult to control. The former depends on many other circumstances and could vary both between different experiments and inside the same one; the latter was intrinsically contained inside the procedure as movement was one of the three principal investigated variables. So, the conclusion was that this metric should probably be removed also from future experiments following a similar protocol as it seems impossible to get clean data.

To sum up, both CFS and SCR were removed from subsequent analysis that will thus take into account only the other three measures: questionnaires, PPS and self-localization drift.

6.2 Characterization outcomes

The current paragraph aims to display the results obtained from the form filled during the calibration step, regarding the characterization of the perceived feeling, both in location and type. As before mentioned, preliminary to the experimental phase, the subject was required to judge both where he was feeling the electrical stimulation, covering the interested area over a hand or foot image, and the type of sensation he was experiencing, choosing from a list of 9 feelings (including the "in-loco" one, indicating the strength under the electrodes).

The obtained responses are reported as follows.

The attached image (Fig. 6.1) illustrates the location of sensation reported from participants over limbs representations; the left column regards feet while the right one hands. In either case, the area covered by the subject is reported both for the low

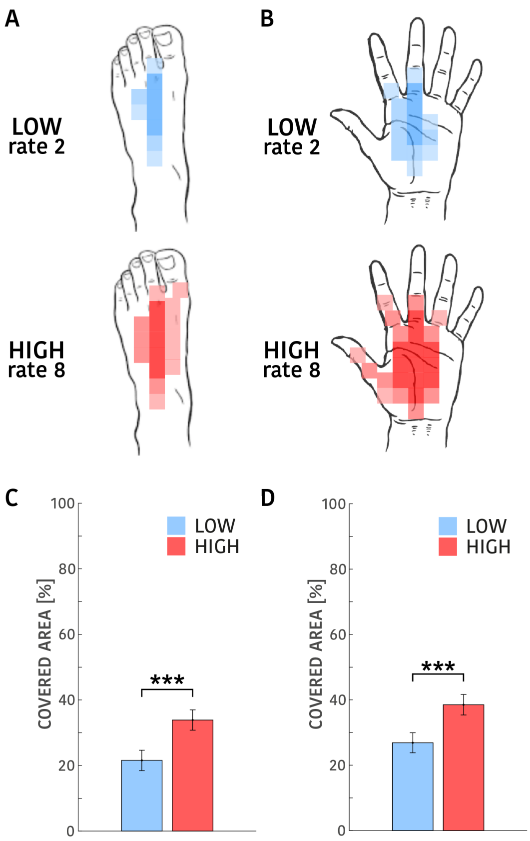


Figure 6.1: ***Location of the sensation***.
In panels A and B, the area colored by subjects as the one where low and high TENS stimulation was felt is shown, for feet and hands respectively. The darker is the color (blue for 2-rated level and red for 8-rated one), the stronger is the feeling. The barplots in panels C and D (referring to feet and hands respectively) report the percentage of the area covered by the electrical input with respect to the whole limb section; in both cases, there is a significant enlargement of the interested region between the two intensity levels. The investigation was done using repeated measures within subjects and then averaging the reported rates among all of them.

and high intensity, in fact, participants were required to fill the form twice during a pulsewidth ramp: when they were feeling a low sensation, rated as 2, and when it was high, rated as 8.

Looking at these images, it can be stated that the area interested from the TENS stimulation enlarges going from low to high intensity in either case. The difference between 2-rated and 8-rated levels is significant as reported from the barplots in panels C and D, showing the percentage of covered area with respect to the whole limb surface; this significance was assessed with post-hoc t-tests (feet p-Value = 3.5275e-05; hands p-Value = 3.5275e-05) using repeated measures within subjects and then averaging the reported rates among all of them.

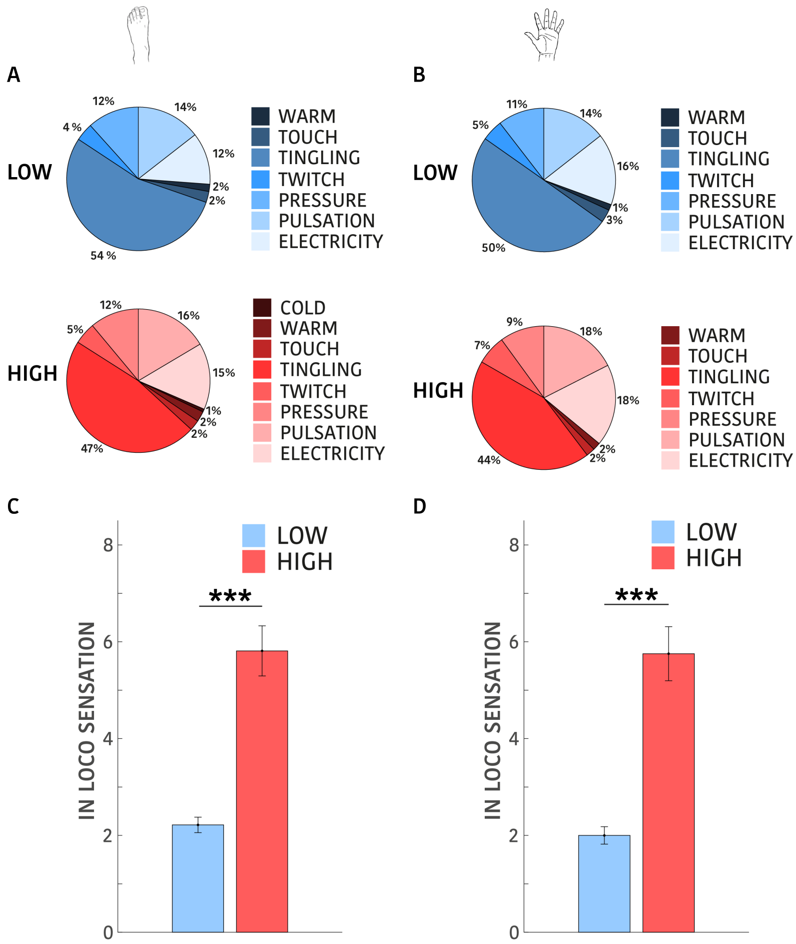


Figure 6.2: ***Type of the sensation.***
The type of sensations reported from subjects in the low and high case is shown in the pie charts in panels A and B: the former regards feet, the latter hands. For each feeling the mean percentage of times it was selected, considering the whole sample size, is reported. The barplot in panels C and D (referring to feet and hands respectively) are instead relative to the "in-loco" stimulation, the one interesting the area directly below the electrodes.

The second characterization figure (Fig. 6.2) is relative the type of sensation reported from participants. While filling the form they are asked to indicate which ones they experience, selecting from: pressure, twitch, tingling, touch, warm, cold, pain, electricity and pulsation. Then, considering the whole calibration runs set, it was possible to retrieve, for each specific feeling, a percentage indicating the number of times it had been selected. Subsequent analysis averaged these quantities over the whole sample size, obtaining the mean percentage of times a sensation was selected.
Similarly to before, results are reported dividing between feet and hands and between low and high intensity.

From graphs in panels A and B it can be retrieved that for all the 4 conditions (feet and hands, low and high) the most common feeling was tingling (close to 50%), followed by pulsation, electricity and pressure (between 9-18Moreover, in panels C and D it is reported the strength, on a scale from 0 to 10, that was experienced "in-loco", indicating the area exactly below the electrodes. The former barplot regards feet, the latter hands: in either case, the perceived intensity is higher in the 8-rated level compared to the 2-rated one and this difference is significant (feet p-Value = 3.9539e-05; hands p-Value = 3.8210e-05). The conclusion is that increasing the delivered current, the sensation detected in the peri-electrodes zone is stronger, as it could be expected. Ideally, the smaller this value the better, reminding that in this protocol the sought-after feeling is a somatotopic one, suggesting that it should not remain under the electrodes delivering it but spread wider through nerve branches.

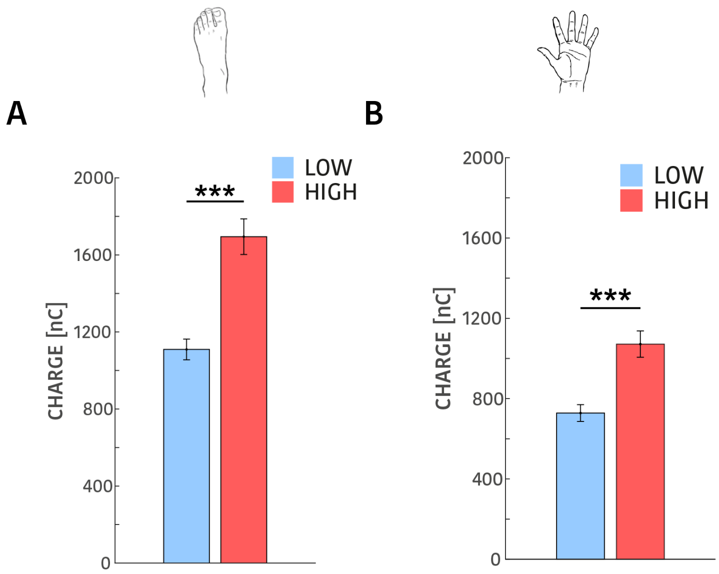


Figure 6.3: ***Charge level.***
Charge value is calculated as the product of amplitude and pulsewidth found during calibration step and it is reported in barplots, both for low and high level, in panels A and B: the former regarding feet, the latter hands. In either alternative, there is a significant increase of charge between the two intensity levels, as expected.

An additional information gathered during the calibration step regards the charge level and is described in the previous figure (Fig. 6.3). During this step anticipating the experiment running, both current amplitude and pulsewidth values that would be used during the trial were defined and, from these, charge computation was possible too as it is the product of amplitude and pulsewidth; considering that this latter value changes between low and high intensity, two different charge levels were determined as well. Panel A reports the barplot for feet, panel B for hands: in both cases charge is bigger in the high level compared to the low one, as expected, and this difference is significant (feet p-Value = 2.6843e-05; hands p-Value = 2.6987e-05).

6.3 Experimental results

A summary of the results obtained from the practical runs of this protocol is here presented, together with a post-hoc statistical analysis.
As many different stimuli combinations were tested, a lot of numerical outcomes were gathered; for a better understanding, they will be reported following the main questions that the experiment was addressing. Each one involves a comparison between 2 or more conditions and reports values and graphs of the 3 reliable metrics: embodiment questionnaire, Peri-Personal Space and self-localization drift. These data are used to answer the experimental question and get an insight about the FBI principles.
So, this results paragraph will be divided in sub-sections, each one relative to one investigated detail.

6.3.1 Visual Only effects

The present comparison tests the effect of the visual only condition where, as explained earlier, the participant was located in the virtual room with the avatar in front of him and no tactile stimulation (and visual corresponding as well) was delivered.
It involves a threefold comparison: visual only, synchronous classical stroking (FBI sync) and four-limbs synchronous TENS without movement (TENS sync).

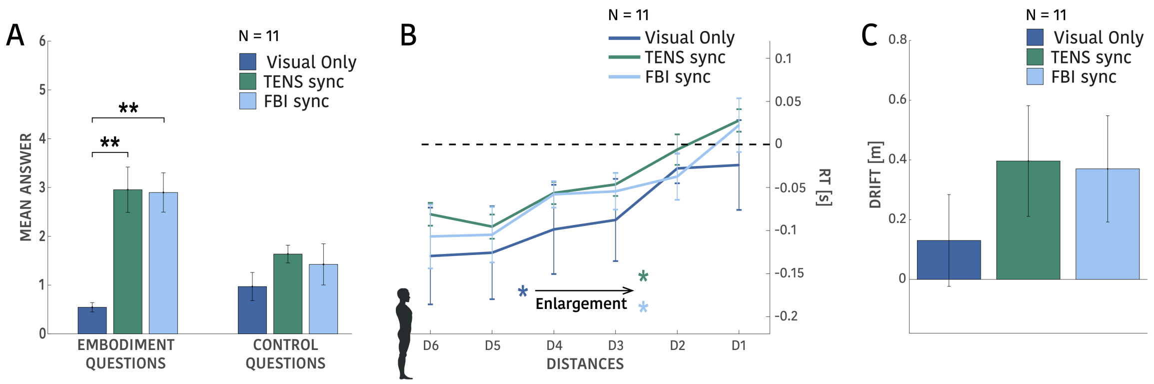


Figure 6.4: ***Results of comparison between visual only, synchronous TENS and synchronous classical stroking***.
Embodiment questionnaire answers (A) are reported averaging among participants; a significant higher embodiment is noticed for TENS sync and FBI sync with respect to visual only (p = 0.0017, p = 0.0016 respectively). For PPS measure (B), normalized RTs (with subtracted baseline) as a function of distance are plotted; a general ascending trend is observed, with the boundary of the PPS located between D2 and D3 for the 2 synchronous condition, and between D4 and D5 (closer to the subject) for the visual only one. The last graph (C) is relative to the drift measure where higher values characterize both TENS sync and FBI sync, but no significant differences were registered.
"", "**" and "***" indicate $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.*

Results

In the three panels (Fig. 6.4), N = 11 indicates the sample size of the considered investigation, which corresponds to the number of subjects belonging to the "movement off" group: 13 originally, then 11 after excluding the 2 subjects because of their low rating on the Body Awareness Questionnaire (Sec. 4.4).

An overview of embodiment questionnaire results is reported in panel A (Fig. 6.4). On the y-axis there is the mean value of the responses obtained joining all the subject but adding 3, so that the final scale is shifted from [-3, +3] to [0, 6]. The x-axis, instead, distinguishes between embodiment and control questions: these latter are those queries supposed not to be related with the particular investigated condition and so no significant differences are expected in this case; differently, a link with the considered condition is supposed to persist for the embodiment ones.

In the questions list reported in Appendix A, "control questions" correspond to Q3, Q8 and Q11, while "embodiment questions" are all the other ones. This term is used to refer to all those items (comprising a total of 8 elements) which include the 4 questionnaire components listed before in the text (Sec. 4.2.2): ownership, self-location, touch and agency. In both cases the reported value was obtained considering a unique

questionnaire averaging all participants answers and then doing the mean of the items belonging to each group: 8 for the embodiment questions, 3 for the control ones.
From statistical analysis, a significant difference was found between the mean ratings of visual only and TENS sync (p = 0.0017) and between visual only and FBI sync (p = 0.0016), but not between TENS and FBI sync (p = 0.9997). From this, it can be concluded that, at least subjectively, both synchronous conditions were able to induce the body illusion as a higher grade was given to the embodiment in these two cases without relevant differences; differently, a significant lower embodiment was associated to the visual only circumstance compared to the others, suggesting that in this case the illusion was not set up.
Considering instead control questions, no significant gaps were highlighted between the three alternatives, as expected (p = 0.3875 for visual only/TENS sync, p = 0.6222 for visual only/FBI sync and p = 0.9215 for TENS sync/FBI sync).

In panel B (Fig. 6.4) the PPS trend for the 3 conditions is plotted: on the x-axis there are the different distances indicating the ball position when the electrical stimulus is given (with D6 being the one closer to the subject), while the y-axis reports the Reaction Time (RT) that it takes the subject to respond to the electrical pulse delivered during the acquisition of this metric. The RTs are normalized with respect to baseline, meaning that its value was subtracted from the experimental ones so that baseline in the reported graph corresponds to zero (horizontal line). In particular, as baseline trials were conducted for distance D1 and D6 (previously explained in Sec. 4.2.1), here for each subject the fastest value (between the one at D1 and the one at D6) was taken into account in order to select the more conservative alternative.
The three curves have an ascending tendency, with a decreasing value going from D1 to D6, meaning that the closer was the ball, the faster was the reaction of the subject to the electrical pulse.
This is perfectly in line with what was demonstrated in literature: the presence of a second stimulus (visual, represented by the looming ball here) speeds up the reaction to a different one (tactile) when the former is inside the PPS [40]; indeed, it was defined as the area where multisensory integration takes place.

The aim of the following analysis over the gathered data was to identify at which distance from the body the PPS's boundary was located. It was done by comparing experimental and baseline data points, similarly to previous studies [28, 40]: the farthest distance from the body at which the visual stimulus significantly speeded up tactile processing, compared to baseline unimodal trial, was taken as proxy of individuals' PPS boundary. This is the spatial location where the external stimulus (visual) interacts with tactile processing on the body, resulting in smaller RTs compared to the baseline condition where the additive visual input was absent. The position in space where this boundary was located was marked with an asterisk on the graph.
In the current case, the margin was placed between D4 and D5 for the visual only condition (significant difference from baseline, $p = 0.0421$) and between D2 and D3 for the TENS sync and FBI sync ones (significant difference from baseline, $p = 0.0059$ and $p = 1.1357e\text{-}4$ respectively) (Fig. 6.4). This demonstrates that an enlargement of the PPS happened in these two latter conditions which, considering previous literature [28], indicates that they were creating a Full Body Illusion while the same cannot be stated for the visual only one. Thus, it rules out the possibility that the sole vision of the avatar can induce embodiment feelings towards an avatar, confirming the necessary integration of two different kinds of stimuli.

In panel C (Fig. 6.4) the distance (in meters) where the individual localizes himself with respect to baseline is reported. It is here recalled that baseline was collected at the beginning of the test, submitting the drift task to the participant before all the trial conditions; then, experimental data were normalized by subtracting this value. The resulting quantity is called proprioceptive drift and a higher level indicates that the subject is localizing himself closer to the avatar, denoting the occurring of an embodiment illusion.
In this case, looking at the reported graph, it is possible to notice a trend, with a taller bar for the two synchronous condition compared to the visual only one but no significant differences were found (all $p > 0.05$) and so, this information cannot be used to state whether a body illusion was taking place or not.

Discussion

Talking about questionnaire answers, the high embodiment rating registered for the FBI sync is not a surprising outcome as it is in line with previous literature [8, 25] but confirms that a synchronized visuo-tactile stimulation induces an ownership feeling towards the external body also with this different platform.

What is more interesting is that more or less the same outcome was obtained considering TENS sync, in fact, almost no difference between the two embodiment values was obtained. This denotes that the visuo-tactile congruence induced a body illusion, regardless of the type of visual and tactile stimuli. Indeed, compared to the classical experiments, here three main differences could be outlined: first of all, the limbs of the individual were stimulated instead of the back; secondly, the stick touch was substituted with an electrical sensation and, consequently, the vision of an identical stick over a virtual body was substituted with some white stripes sliding over its limbs; finally homology was not present anymore. This last point is particularly relevant as, besides using a different kind of stimulation, the implemented visuo-tactile pattern was not homologous, meaning that what the subject was perceiving was not exactly the same thing he was looking at: in fact, he was receiving a current over his limbs while seeing some wavy lines over the avatar's ones. This was due to the fact that the electrical stimulation is something intrinsically not representable and, as a consequence, an identical visual rendering was not possible. The idea in this case was not to reproduce the provided stimulation but the feeling it provoked; as most of the subjects experienced the current input as a mix of tingling and vibration, some wavy sliding stripes seemed a valid alternative.

To sum up, it can be stated that, based on individuals' subjective reports, also a synchronous visuo-electrical stimulation can induce the ownership illusion similarly to a visuo-tactile one.

Differently, while going through the visual only session, participants reported a significant lower embodiment, indicating that in this case they were conscious of their body as distinct from the avatar and no identification with this external figure was taking place. It rules out the possibility that a body illusion could be induced only by staring at an external character without other sensorial inputs, highlighting the necessity of

multisensory integration of 2 or more stimuli. Thus, this represents the key element ownership illusions ground on, both considering full-body or limbs ones.
Examining PPS plots (Fig. 6.4, panel B), similar conclusions can be driven. In effect, a farther PPS limit characterizes the two synchronous condition (between D2 and D3 for both), while it is reduced in the no-stimulation alternative (between D4 and D5). Based on literature assumptions [28], the interpretation is that a personification with the virtual body occurred both in the TENS and FBI synchronous conditions, where a PPS shift in the front space was observed, but not in the visual only one.
To conclude, no strong statements can be made using self-localization data as significance was not achieved. The bigger proprioceptive drift detected in the two synchronous conditions compared to the visual only one suggests that the avatar embodiment was occurring in the former cases but not in the latter one; however, no absolute conclusions can be driven as this difference is not remarkable.

6.3.2 Classical Full-Body Illusion reproduction

This comparison was driven in order to test whether the current protocol was able to reproduce the classical FBI experiment, where the participant was touched with a stick on his back while seeing an identical object moving over a virtual body. Its replication in this platform was as close as possible to literature [8, 25], with the experimenter touching the back of the individual while he was looking at a stick in VR moving over the avatar.
Also in this case, both synchronous and asynchronous conditions were assessed and compared in order to see whether same literature outcomes could be obtained.

Results

Results are reported with the same format used for previous ones. The first image (Fig. 6.5, panel A) refers to the embodiment questionnaire results where a significant higher value was found for the synchronous case with respect to the asynchronous one

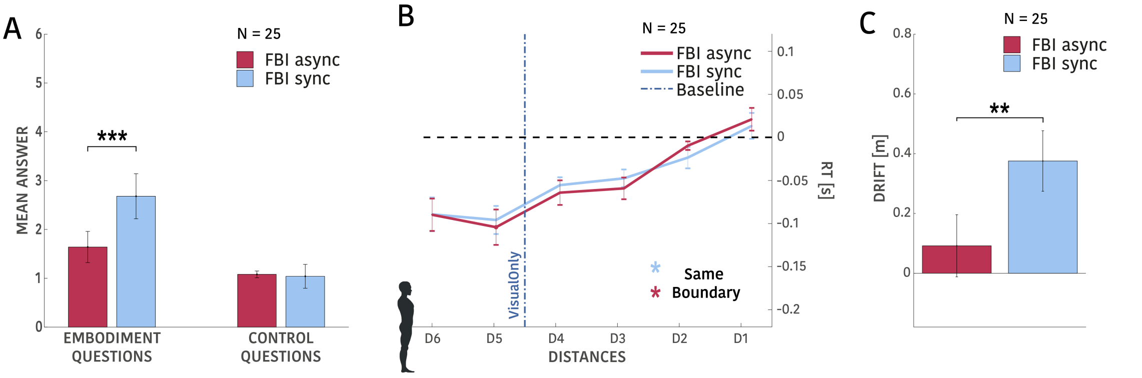


Figure 6.5: ***Results of comparison between synchronous and asynchronous back-stroking.*** *Embodiment questionnaire answers (A) are reported averaging among participants; a significant higher embodiment is noticed for the synchronous alternative with respect to the asynchronous one (p = 1.6333e-4). For PPS measure (B), baseline-normalized RTs as a function of distance are plotted; a general ascending trend is observed but the boundary of the PPS is located at the same level (between D2 and D3) for both conditions. The last graph (C) is relative to the drift measure where a significant higher value was found in case the 2 stimuli were congruent (p = 0.0058), indicating a mis-localization closer to the virtual body.*
“”, “**” and “***” indicate p < 0.05, p < 0.01 and p < 0.001 respectively.*

(p = 1.6333e-4), while no significant difference was obtained considering control questions (p = 0.5422). This results are in line with literature experiments [8, 25] and suggest that, on average, participants elaborated a feeling of ownership only when the two stimuli were congruent, underlying the relevance of multisensory integration.

Considering PPS results (Fig. 6.5, panel B), RTs were normalized subtracting baseline and a general decreasing trend was registered at smaller distance, as seen before. Using the same method explained above, PPS boundary was found at the same distance, between D2 and D3, for both conditions (significant difference from baseline, p = 1.1357e-4 and p = 9.2119e-5 for synchronous and asynchronous respectively).

This outcome is not in line with previous studies involving FBI and PPS recording, which noted an enlargement of the PPS size when the illusion was occurring (synchronous) with respect to when it was not (asynchronous) [28].

Going to proprioceptive drift data (Fig. 6.5, panel C), differently to before, a significant difference was recorded in this case (p = 0.0058), with the subject localizing himself significantly closer to the avatar in the synchronous case with respect to the asynchronous one. This mis-perception of the own body in the front space is a clear sign of identification with the avatar, which supports the conclusions previously driven considering questionnaire answers.

Discussion

When comparing the synchronous and asynchronous stroking, the addressed research question is about the ability of the implemented protocol to recreate the Full-Body Illusion experiment found in previous researches [8, 25]. Based on the gathered results, this reproduction is assessed: it is valid in case subject's answers are in line with literature outcomes, otherwise, some errors occurred while relocating it in a Virtual Reality environment.

In this case, considering questionnaire responses, the significant stronger embodiment obtained when the stimulation was congruent confirms previous studies' assertions about the illusion taking place only in this case and not in the incongruent one. So, it can be stated that, at least subjectively speaking, this scenario can be used to conduct a FBI induction.

The same reasoning can be inferred when looking at proprioceptive drift results; in fact, a significant difference subsists between the self-positioning in the two conditions, with the participant perceiving his body remarkably closer to the avatar in the synchronous condition with respect to the asynchronous. This identification of the own body as translated in the front space indicates an ongoing personification with the virtual body, rightly positioned in front of the subject.

Therefore, also this objective metric argues that a valid reproduction of the classical FBI trial was carried out.

Unfortunately, PPS plots are not in line with literature considerations. In fact, Noel et al. [28] affirmed that PPS boundary was translated toward the virtual body during an illusory identification with it, thus when measured after the synchronous condition with respect to the asynchronous one. The relocation obtained in the former option was justified by saying that the occurring illusion was projecting the participant in the front space and so, shifting his PPS from being centered at the actual location of the physical body to being centered at the subjectively experienced location of the self.

In the presented example, however, no significant differences were found, averaging among participants, between the two conditions and the PPS boundary was located at the same distance (between D2 and D3).

Multiple reasons could cause this behaviour; it may be, for example, that when touching

the individual's back, the experimenter was not exactly matching in time and location the stick moving over the avatar in VR. The strength of the asynchronous would be reduced in this case, making its difference from the synchronous alternative smaller and so not acknowledged by the PPS measure, which is a solid metric.
In fact, one of the biggest issues of the human delivered stimulation is its being poorly controllable, which makes it hard for the experimenter to regulate its parameters: timing, location and intensity. Practically speaking, it is really demanding, by simply looking at a stick moving over the avatar, to reproduce an identical feeling on the real subject (synchronous case) or an opposite one (asynchronous case). The consequence is that the 2 alternatives are not dissimilar enough to permit the participant to spot significant differences between them.
This is also one main reason justifying the rationale of the current project that substitutes the human touch with electrical pulses; these latter are, indeed, easily supervised and a fine regulation of their characteristics (amplitude, frequency and pulsewidth) is allowed.

6.3.3 Validation of electrical stimulation

Another parallel is presented in the upcoming paragraph dealing with the introduction of a new kind of input (TENS), instead of the classical touch, for the FBI induction. The research question is whether also this different stimulation is able to induce the embodiment feeling and, in case of positive answer, whether it respects the same principles observed for the visuo-tactile pattern.
In order to do so, the same comparison undertaken in the literature experiment (synchronous vs asynchronous) is here repeated but using an electrical stimulation; in particular, the 4 limbs one is considered.

Results

Results are reported with the same format used for previous ones. In the first part (Fig. 6.6, panel A) a significant stronger embodiment was reported from subjects dur-

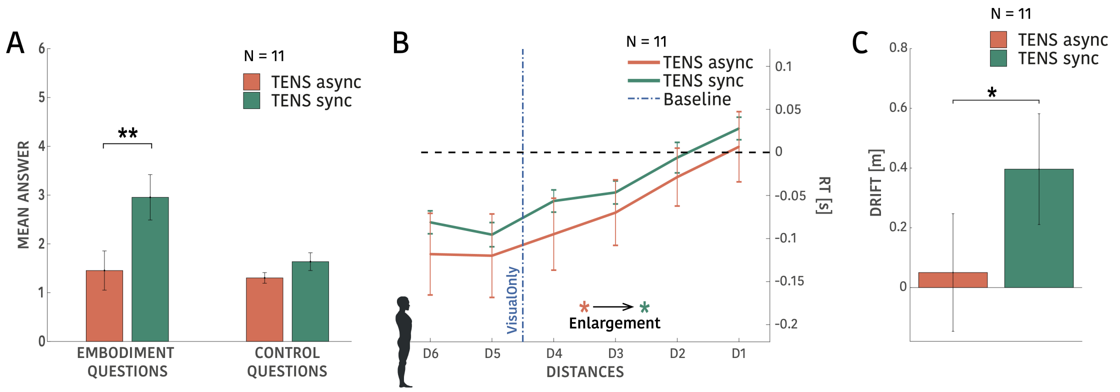


Figure 6.6: ***Results of comparison between synchronous and asynchronous TENS***. *Embodiment questionnaire answers (A) are reported averaging among participants; a significant higher embodiment is noticed for the synchronous alternative with respect to the asynchronous one ($p = 0.002$). For PPS measure (B), baseline-normalized RTs as a function of distance are plotted; a general ascending trend is observed and the boundary of the PPS is located between D3 and D4 for the asynchronous condition and between D2 and D3 for the synchronous one, demonstrating an enlargement in this latter option. The last graph (C) is relative to the drift measure where a significant higher value was found in case the 2 stimuli were congruent ($p = 0.0299$), indicating a mis-localization closer to the virtual body.*
"", "**" and "***" indicate $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.*

ing the synchronous session compared to the asynchronous one ($p = 0.002$), while no relevant differences were registered in control questions ($p = 0.2969$). This shows that an embodiment is felt by the subject in the matching-stimuli case and not the non-matching one, which is in agreement with the FBI functioning, both the one learnt from literature [8, 25, 42, 44] and the one observed in the earlier comparison of the current protocol (Sec. 6.3.2).

In addition here, oppositely from the previous comparison (Sec. 6.3.2), a significant difference between synchronous and asynchronous was recorded in the PPS metric too. In fact, after having normalized RTs subtracting baseline, the bounds of this region (Fig. 6.6, panel B) were located between D2 and D3 in the congruent condition (significant difference from baseline, $p = 0.0059$) while between D3 and D4 in the incongruent one (significant difference from baseline, $p = 0.0463$). So, a shift is noticed in the former condition, suggesting that an illusory ownership is experienced in this case and not in the latter one.

The last graph (Fig. 6.6, panel C), reporting proprioceptive drift values, confirms what have just been remarked, displaying a higher bar in the synchronous case compared to the asynchronous ($p = 0.0299$). Thus, in the first option the subject located himself closer to the virtual body, demonstrating that ownership towards this figure was perceived; unlikely, the same cannot be said for the second option.

Discussion

The present parallel regarding synchronous and asynchronous electrical pulses addresses the main experimental investigation over the possibility of recreating a Full Body Illusion with a TENS stimulation. In case the same outcomes observed in literature back-stroking tests were reproduced in this session, it could be stated that also electrical nerve stimulation can create an illusory embodiment, demonstrating the hypothesis of the project.
The significant higher embodiment revealed from participants during the synchronous TENS condition, compared to the asynchronous one, supports the main assumption, telling that the body illusion was induced in the former but not in the latter case and so, even if the used input was different, a similar FBI, observing the same functioning rules, was generated.
The same conclusion can be driven when considering PPS measure as an anterior shift of its limit was registered in the synchronous condition, revealing an identification with the avatar [28].
The crucial point here is that the relocation of the PPS limit in the synchronous circumstance is observed when the body illusion was induced with TENS (current comparison) but not when back stroking was used instead (previous comparison, Sec. 6.3.2). It is the fine regulation allowed over the electrical stimulation that can justify its being able to generate a detectable difference between the two condition, perceived from the PPS metric too, in contrast with the poorly-controlled human delivered stimulation.
The fact that the combination of TENS and VR can produce a PPS relocation during the FBI can be used as main argument when supporting the implementation of this new platform as a substitute of the classical back stroking experiment.
The higher strength of the asynchronous TENS with respect to the asynchronous stroking was verified with a supplementary test (reported in Appendix D.1) where a threefold comparison was analyzed: visual only, asynchronous TENS and asynchronous classical stroking. Considering all the 3 reported metrics (results are displayed with

the same format), asynchronous TENS behaved similarly to visual only and, assuming that the latter does not induce a body illusion, as demonstrated before (Sec. 6.3.1), the same can be stated for the asynchronous electrical stimulation. A different scenario, instead, was noticed for the asynchronous stroking, in fact, with respect to visual only, a significant gap was present both in the embodiment questions and in the PPS boundary; so, even if this option did not induce a phenomenon comparable to that caused by the synchronous ones, it is also not able to destroy it as the visual only case.
In conclusion, going back to the synchronous/asynchronous TENS comparison, referring to drift data, a significant higher shift of the self-location in the front space was registered during the former condition with respect to the latter one. This again sustains what was demonstrated by the other metrics: a TENS stimulation can induce the FBI and the resulting phenomenon observes the same behaviour found in literature experiments.

6.3.4 Effect of number of limbs

Going through project novelties (Sec. 3.1), the evaluation of the stimulation's extension was marked as one of the bullet points, as 2 different alternatives were tried: the current was given either to just 1 limb (right foot) or to all the 4 limbs, and, as a consequence, the visual stimulus (white lines) was seen either on the right foot of the avatar or on its 4 limbs, respectively.
In the current paragraph these 2 options are compared in order to evaluate whether any significant difference exists between them and so, whether the extension of the stimulation impacted in any way the resulting FBI.
When talking about synchronous and asynchronous TENS in the previous comparisons, it was implied that the current was delivered to all the 4 limbs and so, what is already clear here is that an electrical synchronous stimulation to 4 limbs was able to induce a FBI following the same principles as the one induced in literature with back stroking (Sec. 6.3.3).
Starting from this, the subsequent parallel regards the synchronous TENS to 4 limbs

and to 1 limb with the aim of checking whether this latter condition behaves as the former one (already evaluated). In case of positive answer, the conclusion would be that the stimulation's extension has no impact, while an effect would be instead present in the opposite case.

Results

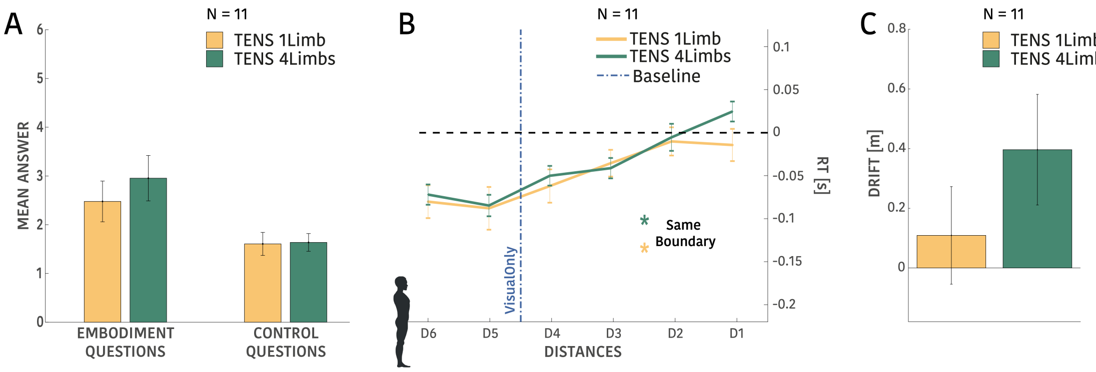


Figure 6.7: ***Results of comparison between synchronous TENS to 1 limb and to 4 limbs****.* *Embodiment questionnaire answers (A) are reported averaging among participants; no significant differences are noticed both in the embodiment and control ratings. For PPS measure (B), baseline-normalized RTs as a function of distance are plotted; a general ascending trend is observed and the boundary of the PPS is located at the same level (between D2 and D3) for both conditions, demonstrating no remarkable dissimilarities in this region's size. The last graph (C) is relative to the drift measure where no relevant distinction is found as well, indicating a similar self-localization. "*", "**" and "***" indicate p < 0.05, p < 0.01 and p < 0.001 respectively.*

Results are reported with the same format used for previous ones. In the first part (Fig. 6.7, panel A) no significant dissimilarities both in the embodiment and control answers were found ($p = 0.1149$ and $p = 0.8594$, respectively). This means that a similar ownership illusion was induced in both cases, taking for granted that the synchronous electrical stimulation to 4 limbs generated this phenomenon, as previously demonstrated (Sec. 6.3.3). Thus, the stimulation's extension did not influence the participant on the subjective perception of the own body and the avatar's one.

Considering RTs trend of the PPS metric (Fig. 6.7, panel B), after subtracting the baseline similarly to before, an ascending tendency is observed as moving farther from the subject and the PPS boundary was computed following the same method as before. Here the limit is positioned at the same level, between D2 and D3, for both conditions (significant difference from baseline, $p = 0.0457$ and $p = 0.0059$ for 1 and 4 limbs case respectively). This indicates that the extend by which the subject projected

himself towards the avatar was comparable in the 2 alternatives, revealing a similar embodiment.
The same conclusion can be driven focusing on the self-localization data (Fig. 6.7, panel C), as a higher value of the proprioceptive drift was registered in the 4 limbs case but the divergence was not remarkable ($p = 0.0903$). Therefore, as significance is not reached, the 2 levels cannot be considered as different and so the self-positioning of the subject, indicating the strength of the personification with the avatar, is equivalent.

Discussion

The comparison here reported regarding synchronous TENS to 1 and 4 limbs answers the research question about the influence that the extension of the electrical current has on the resulting FBI.
The similar embodiment level registered with qualitative reports in both conditions (no significant difference, $p = 0.1149$) tells that an equivalent identification with the avatar was induced regardless of the stimuli location and extension. So, the subjective feelings towards the avatar were not altered by the particular sessions the individual was undertaking.
Similarly, the shift of the PPS was identical in both cases as its boundary was drawn at the same distance (between D2 and D3), denoting a likely projection towards the virtual body. This reasoning is supported by proprioceptive drift values too, in fact, as the registered gap between them was not significant, they tell that the subject was more or less self-positioning at the same point in space.
To sum up, it can be stated that no significant difference exists in the illusion induced with 1 or 4 limbs (already assessed in Sec. 6.3.3), meaning that the stimulation extension did not impact on it.
This is a really interesting result considering the possibility of using this platform for people with limb impairments, such as post-stroke patients, for who it may be not possible to have a 4 Limbs stimulation. In this case only 1 limb would receive current but there would be no difference in the resulting FBI. These subjects are characterized not only by motor impairments but also sensorial ones [21]: somatoparaphrenia or emilateral neglect are examples of conditions that can be observed in such individuals.

The former refers to the absence of awareness that a limb or a body part is owned by the self, meaning that the subject thinks it belongs to someone else; the latter, instead, is a condition in which one is not conscious of half of his body, not able to perceive it, even if capable to see it.
The advantage of inducing an illusory embodiment in such subjects would regard both sensorial and motor deficits, because while taking the experiment the participant both receives a current to his limbs while seeing the avatar's ones stimulated and notices the movement of his body parts reproduced by the virtual ones. This would induce both ownership and agency feelings towards the avatar with the consequent positive outcome of helping the motor recovery and also the regain of awareness towards his limbs.

6.3.5 Effect of movement

The introduction of movement as investigated variable does not really represent a novelty, because its effect has been already studied in some previous experiments [12, 22], also in combination with Virtual Reality. The novel element here is its combination with TENS, aiming to test not only the ability of movement to induce a body illusion, which has been already demonstrated [18, 44], but its effect in addition to the TENS stimulation.
For this reason two different comparisons are presented in this paragraph:

1. visual only and the movement only, with the latter being a situation without visuo-electrical stimulation (as visual only) but with movement reproduction (it can be imagined as the "visual only" condition for the movement-on group).
   Its aim is to check whether only movement, without any kind of additional stimulus, can or not induce an ownership illusion;

2. synchronous TENS to 4 limbs with and without movement. Here as well the considered condition is the same (synchronous current to 4 limbs) but in the former data are retrieved from movement-off group while in the latter from movement-

on.

Its purpose is to test the interaction of movement and TENS compared to the electrical stimulation alone.

Results

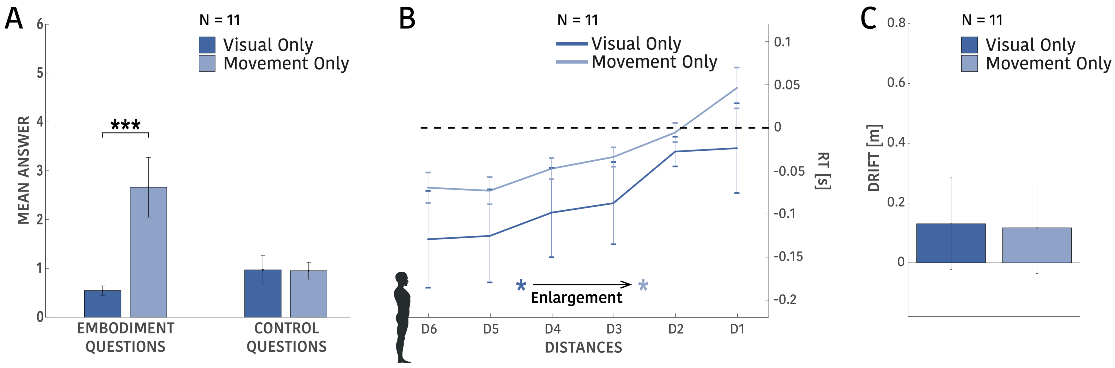


Figure 6.8: ***Results of comparison between visual only and movement only***. *Embodiment questionnaire answers (A) are reported averaging among participants; a significant difference in the embodiment ratings is noticed (p = 9.5710e-6), with a higher value for the movement only condition, while no significant differences are registered for control questions (p = 0.9759). For PPS measure (B), baseline-normalized RTs as a function of distance are plotted; a general ascending trend can be observed and the boundary of the PPS is located between D4 and D5 for visual only and between D2 and D3 for movement only, demonstrating a shift of the region's center towards the avatar for the latter condition. The last graph (C) is relative to the drift measure where no relevant distinction was found (0.9514), indicating a similar self-localization.*
"", "**" and "***" indicate $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.*

Results are reported with the same format used for previous ones. In the first comparison (Fig. 6.8, panel A) a significantly higher embodiment was subjectively reported from participants in the movement only condition with respect to the visual only one (p = 9.5710e-6); no relevant dissimilarities were instead registered in the control answers ($p = 0.9759$). This indicates that, even in the absence of any other input, a subject developed a feeling of ownership towards a virtual body that reproduced all his movements. As could be expected, when considering the sub-components making up the embodiment score (additional results in appendix D.6), the highest-rated one was agency because, seeing his actions repeated by the avatar, the participant experienced control over it. So, the only presence of movement was able to induce a body illusion, as it had been previously demonstrated in literature [18, 44].

Considering the PPS metric (Fig. 6.8, panel B), RTs were normalized subtracting base-

line and a general ascending trend was observed, as in previous cases. The boundary of the region was between D4 and D5 for the visual only and between D2 and D3 for the movement only (significant difference from baseline, $p = 0.0421$ and $p = 0.0093$ for visual and movement only cases respectively). The enlargement observed in the latter condition confirmed what had been previously stated about movement being able, on its own, to generate a body illusion; moreover, the induced phenomenon is similar to the one caused by visuo-electrical congruence because the PPS limit is located at the same distance as in the synchronous TENS condition (both 1 and 4 limbs).
However, this conclusion is not supported by the proprioceptive drift data (Fig. 6.8, panel C), as the self-localization was almost identical in both cases.

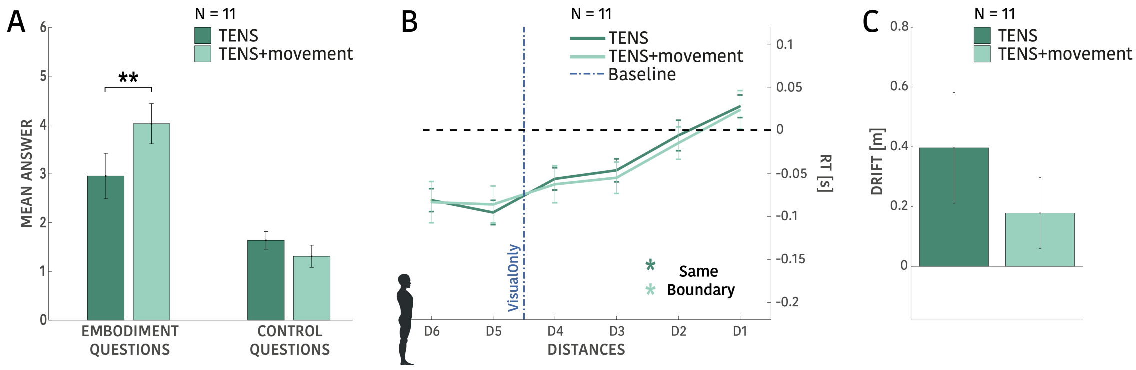


Figure 6.9: ***Results of comparison between synchronous TENS to 4 limbs in movement off and on groups.***
Embodiment questionnaire answers (A) are reported averaging among participants; a significant higher embodiment rating is registered when movement is added to TENS compared to the electrical stimulation alone (p = 0.0086), while no significant differences are registered for control questions (p = 0.5388). For PPS measure (B), baseline-normalized RTs as a function of distance are plotted; a general ascending trend was observed and the boundary of the PPS was located at the same distance (between D2 and D3) for both conditions. The last graph (C) is relative to the drift measure where no relevant distinction was found (0.3126), indicating a similar self-localization.
"", "**" and "***" indicate p < 0.05, p < 0.01 and p < 0.001 respectively.*

Going to the second comparison, in the first part (Fig. 6.9, panel A) a significantly higher embodiment was subjectively reported from participants in the condition where movement was added to TENS with respect to the one where only the visuo-electrical stimulation was present($p = 0.0086$); no significant difference was instead revealed with respect to control questions ($p = 0.5388$). This denotes that the subjective experience of the body illusion was stronger when movement was added to the visuo-electrical congruence.
Anyway, this conclusion is not supported by both objective metrics; in fact, focusing

on PPS data (Fig. 6.9, panel B), it can be seen on the graph of normalized RTs that a general increasing tendency is observed, as expected from literature and previous analysis, but the boundary of the PPS region was placed at the same level, between D2 and D3, for both conditions (significant difference from baseline, $p = 0.0059$ and $p = 0.0099$ for synchronous TENS without and with movement respectively). This suggests that the subject was projected in the front space with a similar strength in either cases, indicating a similar identification with the virtual body. Furthermore, also the second quantitative measure, namely the proprioceptive drift, noticed the same; it is reported in the last graph of the figure (Fig. 6.9, panel C) where a higher value was collected for the condition without movement compared to the one with movement, but the gap did not reach significance ($p = 0.3126$).

To sum up, what can be concluded here is that no objective effects are provoked by the addition of movement to TENS.

Discussion

The two parallels showed in this paragraph aim at evaluating the impact of movement on the FBI with respect both to its ability to generate such phenomenon from nothing and to enhance an already induced one.

Focusing on the first point the considered conditions were the visual only and the movement only, where there was no visuo-electrical stimulation and the difference was just the absence or presence of movement, respectively. As it has been reported in the previous result section (Sec. 6.3.5), a difference was found in the questionnaire answers, with a significantly higher rating in the movement only with respect to the visual only. Assuming this latter scenario as not able to induce a body illusion (previously demonstrated in Sec. 6.3.1), this result proved that, instead, the subjective perception of the avatar as ”own body” was produced by movement reproduction, despite the absence of any other stimulus.

The same was concluded considering PPS results, showing that its margin shifted from being centered between D4 and D5 in the visual only case to being centered between D2 and D3 when movement was added. The boundary of the latter alternative overlaps with the one found in previous congruent conditions (synchronous TENS both

to 1 and 4 limbs), proved to induce an illusory identification (Sec. 6.3.3, Sec. 6.3.4). As the same PPS relocation happened, it can be deduced that the only presence of movement induced an illusion comparable to the one observed with TENS. Unfortunately, no variation was registered in the drift data, with an identical self-localization with and without movement. The fact that this value is really small in both condition involving movement could be justified saying that this metric is altered by the presence of movement. This was sustained also in a recent study [27] that when a person moves, his somatosensory, vestibular and interoceptive signals are updated, reducing the maintenance of the illusory self-location. This is the reason why they criticized the method used in previous studies [23, 25] for drift acquisition (involving participant locomotion), saying that a subject should not move in order to get reliable data; in fact, they developed a new technique, implemented in this protocol too.
However, having both a subjective and an objective metric confirming this, it can be affirmed that an illusory ownership was set on when movement tracking was present, meaning that all participant's actions were real-time reproduced by the avatar. This is not surprising but confirms what had been previously stated in literature [18, 44].

What is more innovative is the second point, comparing synchronous TENS without and with movement, which tests whether the addition of movement can enhance the FBI, already produced by synchronous TENS.
Considering embodiment questions, a higher rating was recorded when movement was added to the sole TENS; however, both quantitative metrics (PPS and proprioceptive drift) did not support this reasoning as no significant differences were detected analysing their data. In addition, taking into account additional results reported in Appendix D.2.6: considering the sub-components of the Embodiment questionnaire, the only one with a significant difference is Agency (as could be expected because of the ability of controlling the virtual body when movement is present), while no significant results are found considering vividness, prevalence and both sub-components of the PCI questionnaire.
Therefore, the following inference was that no objective effects were obtained, with respect to the resulting body illusion, by the addition of movement reproduction to

TENS stimulation. So, the impact of movement, with respect to before, seemed to be decreased here by the presence of the electrical stimulation, probably because of a TENS "ceiling effect", a term indicating that the electrical current already induces a strong phenomenon without enabling any enhancement.
This theory is in line with the "All Or Nothing" principle supported by Ehrsson [44], saying that the body illusion event has a binary nature which means that, once it is induced (in this case making use of TENS), it is not necessary to add any other kind of stimuli (in this case movement) as they will not affect or increase the resulting phenomenon.

A possible critic that could have been moved in this case was that the reduced movement impact caused by TENS presence could have had another explanation, besides TENS ceiling effect. Indeed, it could have been that a wrong interaction between electrical stimulation and movement occurred, destroying the illusion.
In order to run out this possibility, a further comparison was conducted between the movement only and the synchronous TENS with movement. In fact, in case it was the bad interaction of variables and not the TENS ceiling effect the one generating this phenomenon, it would result that the body illusion created in the movement only circumstance is stronger compared to the TENS plus movement one (destroying the illusion); this additional parallel is hereafter reported.

Referring to the figure reported above, a significant difference between movement only and synchronous TENS plus movement was noticed only in the subjective reports (Fig. 6.10, panel A). Here, in fact, a higher rating characterizes the synchronous TENS with movement compared to the movement only, meaning that the illusory ownership was subjectively stronger in the former case.
However, this reasoning is not supported by both quantitative metrics (PPS and drift) which did not register any relevant dissimilarity (Fig. 6.10, panel B and C). The first one drew the PPS boundary at the same level, between D2 and D3, for both the movement only and synchronous TENS with movement conditions (significant difference from baseline, $p = 0.0093$ and $p = 0.0099$ respectively); the second one did not identify a remarkable gap between the two options.

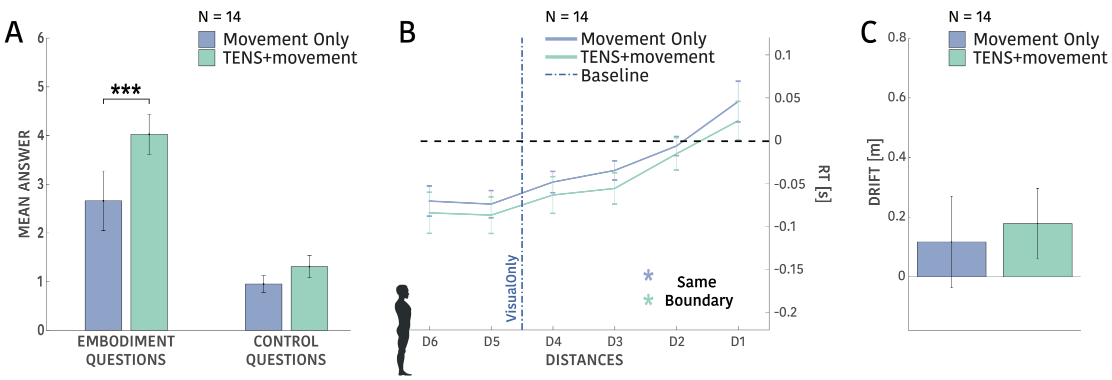


Figure 6.10: *Results of comparison between movement only and synchronous TENS with movement*.
Embodiment questionnaire answers (A) are reported averaging among participants; a significant higher embodiment is noticed for the alternative where TENS is added to movement with respect to movement alone (p = 1.2207e-4). For PPS measure (B), baseline-normalized RTs as a function of distance are plotted; a general ascending trend is observed and the boundary of the PPS is located between D2 and D3 for both cases, demonstrating no enlargement is occurring. The last graph (C) is relative to the drift measure where no significant gap was found (p = 0.4054), indicating an equal mis-localization towards the virtual body.
"", "**" and "***" indicate $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.*

This additional parallel was conducted in order to check whether the reduced effect of movement noticed when TENS was present was caused by a ceiling effect of the electrical stimulation or, instead, by a wrong interaction of TENS with movement. In particular, its aim was to rule out the second alternative; in fact, supposing that was valid, a stronger effect of movement only over synchronous TENS with movement would be expected, as the latter case would destroy the illusion, instead induced by the former one, as previously demonstrated (Sec. 6.3.5).
However, this behaviour is not observed as no significant objective difference subsists between the two cases and so, it can be stated that the reduced effect of movement is really due to a ceiling effect of TENS stimulation.

The final conclusion about movement is that this variable, similarly to the visuo-electrical congruence, could induce a body illusion from scratch but its effect was, instead, decreased when another stimulation source was present. So, in general, it is meaningless to add it to a synchronous TENS stimulation as it cannot increased the already induced phenomenon, as well as it is not useful to sum TENS to the movement reproduction.

Chapter 7

Conclusion and Future works

7.1 Take-home messages

The experimental manipulation of multisensory congruence gave the expected result as it was known from literature that a synchronous visuo-tactile stimulation involving a real subject and a virtual one was able to induce a personification with this figure; while the same could not be stated for an asynchronous one. This was valid both for sessions with the classical stroking and for those involving electrical stimulation: on one hand, it was shown that a reliable reproduction of previous studies was made, on the other one, it was demonstrated that the same Full-Body Illusion (FBI) functioning was observed using an electrical stimulation. This is one of the main take-home messages of this work as sustains the hypothesis which proposes the use of TENS stimulation for a FBI induction.

Another key statement resulting from this project is the description of multisensory integration as the cornerstone of embodiment illusions, highlighting the importance of having two concurrent stimuli to get such phenomenon. This was possible thanks to the evaluation of the baseline condition (visual only), during which no stimuli were provided to the participant, which turned out not to be able to induce a mis-identification experience.

The fact that TENS was proved as being a valid input in body illusion trials opens many possibilities for future studies, allowing to overcome the limits encountered while

going through literature, as it is finely controllable, giving at the same time a high flexibility in its characterization. In fact, it had been here demonstrated that its extension over the body had no impact on the resulting perception, as data gathered when stimulating only one limb or all the four limbs did not differ statistically.
The last relevant findings regard movement, which had been investigated as between-subject variable, dividing participants into 2 groups: one undergoing the sessions with movement tracking and the other without. The reported ownership was significantly higher in the former case, as could be expected from literature [12, 22], with a particularly strong sense of agency and control over the virtual body. However, it was noticed that the impact of movement was weaker when it was added to TENS stimulation and not presented as unique variable. This behavior was determined as being due to a ceiling effect of electrical stimulation, which already induced an effective illusion, combined with the *All Or Nothing* principle by Ehrsson [18, 44], considering the FBI phenomenon as a binary one, which, once induced, cannot be enhanced by adding other stimulation inputs.

7.2 Limitations

Even if many points have been clarified by the presented project, some limitations were met while going through it, which should be overcome by future works. These latter are hereby listed:

1. the total duration of the test (including calibration and experiment) was extremely long, nearly 4 hours, also considering that the participant was required to stand for most of the time. Its negative consequence was that, as time was passing by, subject's attention was decreasing together with the reliability of his answers;

2. the sample size could represent a drawback as well because, even if 25 is an acceptable quantity in this kind of trials, some observed trend could have reached significance with a larger population.

Therefore, in case a similar experiment will be repeated, the recruitment of a higher number of subjects, each one undergoing less conditions, would be suggested.

7.3 Future applications

The presented work shed light to the understanding of the different components involved in the embodiment, in fact, both visuo-tactile or visuo-electrical synchronicity and real-time motion tracking were able to influence the perception of the own body, leading in some cases, to an illusory one.
This particular experience could be usefully induced in participant with limb impairments, such as post-stroke patients, who deal with both motor and sensorial impairments [21]: the former regard their inability of completely move or finely control their arms and legs while the latter regard the perception of such body parts. Examples of pathologies noticed in these patients are: somatoparaphrenia, when the individual is not conscious that a body part is of his own and thinks it belongs to someone else or emispatial neglect, when one is not aware of half of his body, even if he can clearly see it with his eyes [7].
The proposed protocol could be used with these patients either as measure or treatment. In the former case, it would be employed to qualitatively and quantitative measure the subject perception and awareness towards his body and then, gathered data could be used for a pre/post treatment parallel (in case he is undergoing a therapy) or compared with the ones from healthy subjects, to evaluate how embodiment changes with the disease. In the latter one, instead, the treatment itself could be delivered through this protocol. A possible one to implement is the constraint therapy which consists in forcing the subject to use the compromised limb, for example by tracking only the movement of this limb and limiting the balls-catching task just around it. The aim is to improve patient's motor skills and help him in regaining awareness towards the impaired body part, activating it and seeing these movements reproduced by the avatar. Compared to the mirror-therapy, already diffused in post-stroke rehabilitation, it allows a visuo-electrical matching in addition to the visuo-motor one; it is a significant advantage when considering patients with really compromised motor abilities, for whom a therapy based on motor reproduction would be unfeasible.

Appendix A

Embodiment Questionnaire

Complete list of Embodiment Questionnaire items.

Embodiment questionnaire (scale from -3 to 3)

Q1. I had the feeling that I was looking at my body

Q2. I felt as if the virtual body was my body

Q3. It seemed as if I might have more than one body

Q4. I felt as if my body was located where I saw the virtual body

Q5. I felt as if my (real) body was drifting towards the virtual body

Q6. It seemed as if I felt the stimulation in the location where I saw the virtual body stimulated

Q7. It seemed as if the tactile sensation I felt was caused by the visual stimulus on the virtual body

Q8. It seemed as if the stimulation I felt was located somewhere between my physical body and the virtual body

Q9. I felt like I could control the virtual body as if it was my own body

Q10. The movements of the virtual body were caused by my movements

Q11. I felt as if the virtual body was moving by itself

Vividness and prevalence questions

Q1. Using a scale from 0 to 10 quantify the vividness: how much the illusion of being outside your body was realistic?

Q2. Using a scale from 0 to 100% quantify how long you had the illusion of being outside your body.

Appendix B

Phenomenology of Consciousness Inventory Questionnaire

Complete list of Phenomenology of Consciousness Inventory (PCI) Questionnaire items.

Phenomenology of Consciousness Inventory Questionnaire (PCI) (scale from 0 to 6)

Q1. My body ended at the boundary between my skin and the world / I felt my body greatly expanded beyond the boundaries of my skin.

Q2. My bodily feelings seemed to expand into the world around me / My bodily feelings were confined to the area within my skin

Q3. I continually maintained a very strong sense of separation between myself and the environment. / I experienced intense unity with the world; the boundaries between me and the environment dissolved away.

Q4. I was not aware of being aware of myself at all; I had no self-awareness. / I was very aware of being aware of myself; my self-awareness was intense.

Q5. I was continually conscious and well aware of myself. / I lost consciousness of myself.

Q6. I maintained a very strong sense of self-awareness the whole time. / I did not maintain a very strong sense of self-awareness at all.

Appendix C

Body Awareness Questionnaire

Complete list of Body Awareness Questionnaire (BAQ) items.

Body Awareness Questionnaire (BAQ) (scale from 1 to 7)

Q1. I notice differences in the way my body reacts to various foods.

Q2. I can always tell when I bump myself whether or not it will become a bruise.

Q3. I always know when I've exerted myself to the point where I'll be sore the next day.

Q4. I am always aware of changes in my energy level when I eat certain foods.

Q5. I know in advance when I'm getting the flu.

Q6. I know I'm running a fever without taking my temperature.

Q7. I can distinguish between tiredness because of hunger and tiredness because of lack of sleep.

Q8. I can accurately predict what time of day lack of sleep will catch up with me.

Q9. I am aware of a cycle in my activity level throughout the day.

Q10. I don't notice seasonal rhythms and cycles in the way my body functions.

Q11. As soon as I wake up in the morning, I know how much energy I'll have during the day.

Q12. I can tell when I go to bed how well I will sleep that night.

Q13. I notice distinct body reactions when I am fatigued.

Q14. I notice specific body responses to changes in the weather.

Q15. I can predict how much sleep I will need at night in order to wake up refreshed.

Q16. When my exercise habits change, I can predict very accurately how that will affect my energy level.

Q17. There seems to be a "best" time for me to go to sleep at night.

Q18. I notice specific bodily reactions to being overhungry.

Appendix D

Supplementary Material

D.1 Additional comparison of visual only, asynchronous TENS and asynchronous classical stroking

In this paragraph additional comparisons not presented in the main text are reported.

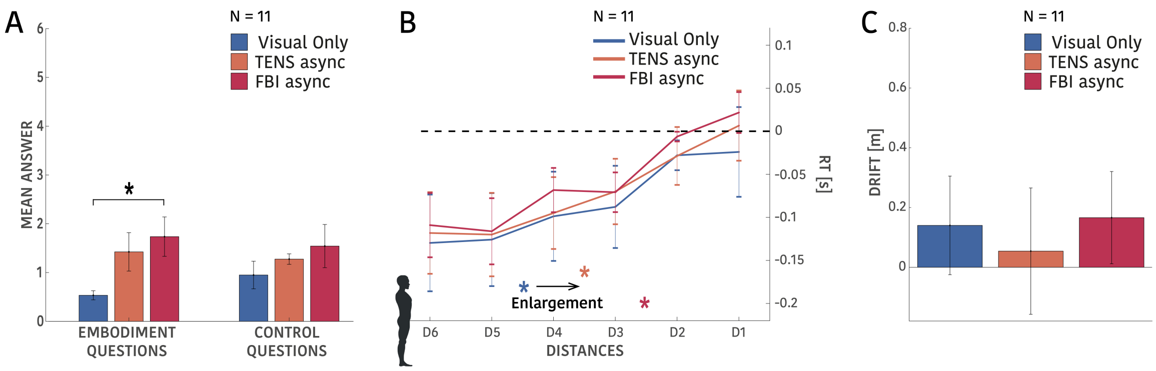


Figure D.1: ***Results of comparison between visual only, asynchronous TENS and asynchronous classical Full Body Illusion.***
Embodiment questionnaire answers (A) are reported averaging among participants; a significant higher embodiment is noticed for the asynchronous classical stroking with respect to the visual only ($p = 0.0372$), while no significant differences are found in the other combinations ($p = 0.0914$ for visual only/async TENS and $p = 0.9291$ for async TENS/async stroking). For PPS measure (B), baseline-normalized RTs as a function of distance are plotted; a general descending trend is observed and the boundary of the PPS is located between D2 and D3 for asynchronous stroking, between D3 and D4 for asynchronous TENS and between D4 and D5 for visual only. The last graph (C) is relative to the drift measure where no significant gaps were found for all combinations ($p = 0.8784$ for visual only/async TENS, $p = 0.9830$ for visual only/async stroking and $p = 0.9488$ for async TENS/async stroking), indicating an equal mis-localization towards the virtual body.
"", "**" and "***" indicate $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.*

Referring to the first part of the figure reported above (Fig. D.1, panel A), a significant difference in the subjective embodiment reports was found between visual only and asynchronous stroking (p = 0.0372), while there are not remarkable contrasts between visual only and asynchronous TENS (p = 0.0914) and between asynchronous TENS and asynchronous stroking (p = 0.9291). Considering PPS (Fig. D.1, panel B), 3 different boundaries were identified (as seen similarly in previous parallels): between D4 and D5 for visual only, between D3 and D4 for asynchronous TENS and between D2 and D3 for asynchronous stroking (significant difference from baseline, p = 0.0421, p = 0.0463 and p = 9.2119e-5 respectively). Finally, going to proprioceptive drift data (Fig. D.1, panel C), no remarkable gaps are noticed, with a similar self-localization in the 3 options (p = 0.8784 for visual only/asynchronous TENS, p = 0.9830 for visual only/asynchronous stroking and p = 0.9488 for asynchronous TENS/asynchronous stroking).

This additional comparison was driven in order to demonstrate the higher strength of the asynchronous TENS with respect to the asynchronous stroking. Considering all the 3 reported metrics, the only difference between asynchronous TENS and visual only was observed in the PPS, with the boundary being located one distance farther from the subject for the asynchronous electrical current (between D3 and D4) compared to the visual only but, anyway, not as far as in the congruent conditions supposed to induce the illusion (between D2 and D3). This suggests that the two alternatives behaves in a similar way and, assuming that the former one does not induce a body illusion, as demonstrated before (Sec. 6.3.1), the same can be stated for the asynchronous electrical stimulation. A different scenario, instead, is noticed for the asynchronous stroking compared to the visual only, in fact, both a significant gap is present in the embodiment questions and the PPS boundary differs of 2 distances; so, even if this option does not induce a phenomenon similar to that caused by the synchronous ones, it is also not able to destroy it as the visual only case.

D.2 Supplementary graphs of reported comparisons

In this paragraph additional graphs regarding comparisons, already reported in the Results section (Sec. 6.3), are displayed.

D.2.1 Supplementary graphs for comparison: visual only, TENS synchronous and FBI synchronous

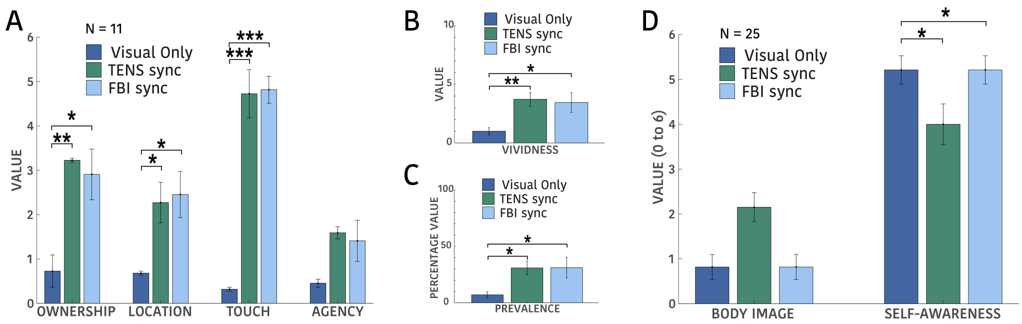


Figure D.2: ***Supplementary results of comparison between visual only, synchronous TENS and synchronous Full Body Illusion*.**
Embodiment questionnaire answers (A) are reported detailing each sub-component, with a significant difference between visual only/TENS synchronous and visual only/FBI synchronous in Ownership, Location and Touch sections. In panels B and C Vividness and Prevalence values are reported respectively, with a significant difference between visual only/TENS synchronous and visual only/FBI synchronous for both. In panel D, PCI questionnaire is reported with its 2 sub-components: Body Image and Self-Awareness; a significant difference is found between visual only/TENS synchronous and visual only/FBI synchronous in the latter section but not in the former one.
"", "**" and "***" indicate $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.*

D.2.2 Supplementary graphs for comparison: FBI synchronous and FBI asynchronous

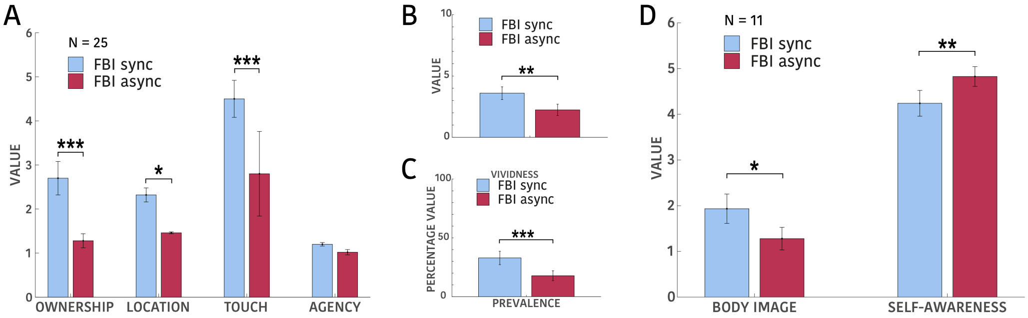


Figure D.3: ***Supplementary results of comparison between synchronous Full Body Illusion and asynchronous Full Body Illusion.***
Embodiment questionnaire answers (A) are reported detailing each sub-component, with a significant difference between synchronous and asynchronous in Ownership, Location and Touch sections. In panels B and C Vividness and Prevalence values are reported respectively, with a significant difference between synchronous and asynchronous for both. In panel D, PCI questionnaire is reported with its 2 sub-components: Body Image and Self-Awareness; a significant difference is found between synchronous and asynchronous in both sections.
"", "**" and "***" indicate* $p < 0.05$, $p < 0.01$ *and* $p < 0.001$ *respectively.*

D.2.3 Supplementary graphs for comparison: TENS synchronous and TENS asynchronous

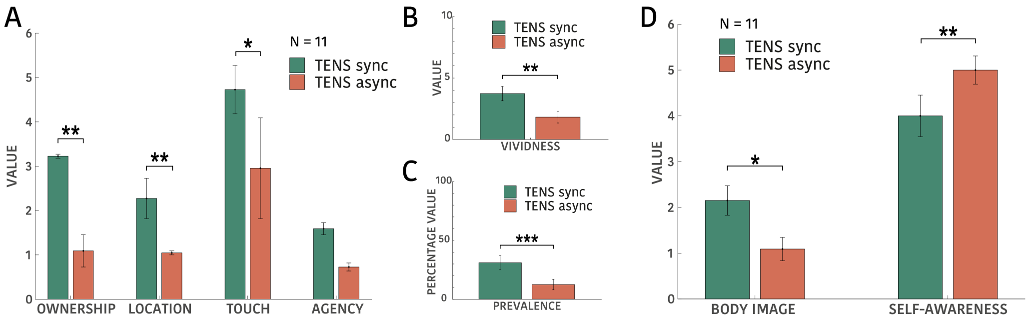


Figure D.4: ***Supplementary results of comparison between synchronous TENS and asynchronous TENS.***
Embodiment questionnaire answers (A) are reported detailing each sub-component, with a significant difference between synchronous and asynchronous in Ownership, Location and Touch sections. In panels B and C Vividness and Prevalence values are reported respectively, with a significant difference between synchronous and asynchronous for both. In panel D, PCI questionnaire is reported with its 2 sub-components: Body Image and Self-Awareness; a significant difference is found between synchronous and asynchronous in both sections.
"", "**" and "***" indicate* $p < 0.05$, $p < 0.01$ *and* $p < 0.001$ *respectively.*

D.2.4 Supplementary graphs for comparison: TENS synchronous to 1 and 4 limbs

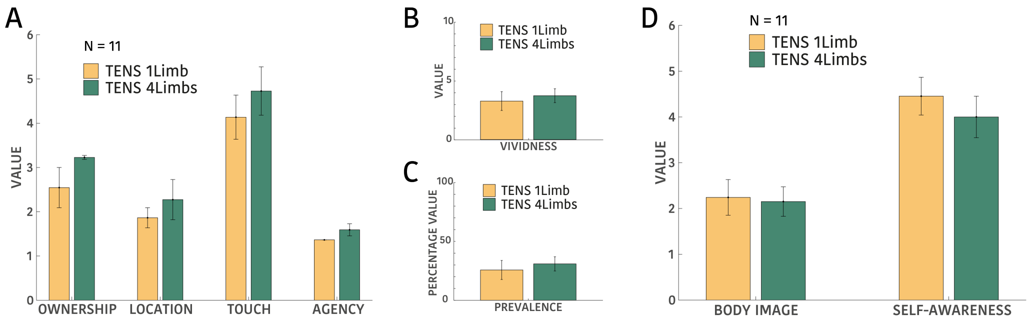


Figure D.5: ***Supplementary results of comparison between synchronous TENS to 1 and 4 limbs***.
Embodiment questionnaire answers (A) are reported detailing each sub-component; no significant differences are found between the two conditions. In panels B and C Vividness and Prevalence values are reported respectively, with no significant differences between 1 and 4 limbs for both. In panel D, PCI questionnaire is reported with its 2 sub-components: Body Image and Self-Awareness; no significant differences are found here as well in both sections.
"", "**" and "***" indicate $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.*

D.2.5 Supplementary graphs for comparison: visual only and movement only

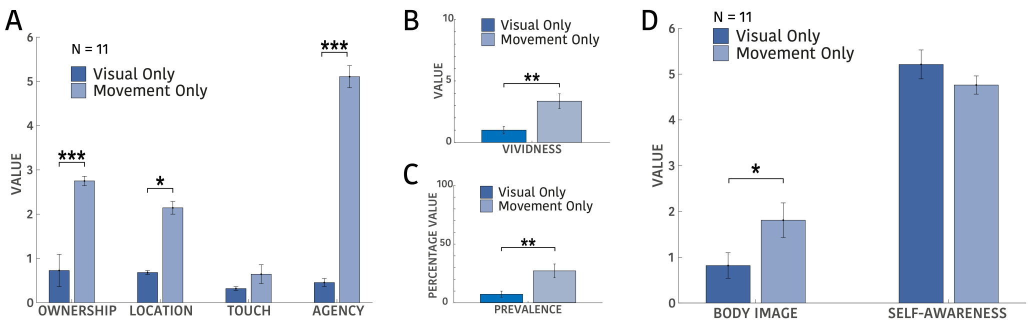


Figure D.6: ***Supplementary results of comparison between visual only and movement only***.
Embodiment questionnaire answers (A) are reported detailing each sub-component with a significant differences in Ownership, Location and Agency sections; this latter in particular displays a huge difference as could be expected. In panels B and C Vividness and Prevalence values are reported respectively, with a significant difference between visual only and movement only for both. In panel D, PCI questionnaire is reported with its 2 sub-components: Body Image and Self-Awareness; a significant difference is found between visual only and movement only in the former section but not in the latter one.
"", "**" and "***" indicate $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.*

D.2.6 Supplementary graphs for comparison: synchronous TENS to 4 limbs without and with movement

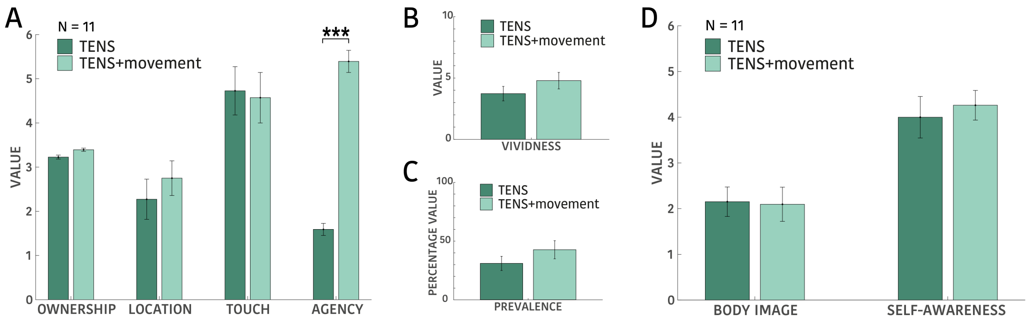


Figure D.7: *Supplementary results of comparison between synchronous TENS to 4 limbs without and with movement*.
Embodiment questionnaire answers (A) are reported detailing each sub-component with a significant difference only in the Agency section. In panels B and C Vividness and Prevalence values are reported respectively, with no significant differences between the presence or absence of movement. In panel D, PCI questionnaire is reported with its 2 sub-components: Body Image and Self-Awareness; no significant difference are found here as well between the two conditions in both sections.
"", "**" and "***" indicate* $p < 0.05$, $p < 0.01$ *and* $p < 0.001$ *respectively.*

D.2.7 Additional Information

Additional video with explanation of experiment sessions available at the following link: VideoExperiment.

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