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L'ÉCOLE CENTRALE DE NANTES

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Sciences de l'Ingénierie et des Systèmes
Spécialité : *Architecture et Études Urbaines*

Par

Martin GUY

Évaluation et Manipulation de l'Incarnation Virtuelle

Projet de recherche doctoral présenté et soutenu à l'Ecole Centrale de Nantes, le 2 février 2023
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Rapporteurs avant soutenance :

Ouriel GRYSZPAN Professeur des universités, Université Paris-Saclay
Jean-Rémy CHARDONNET Maître de conférences HDR, Institut Arts et Métiers de Chalon-sur-Saône

Composition du Jury :

Président :	Simon RICHIR	Professeur des universités, Arts et Métiers ParisTech
Examineurs :	Ouriel GRYSZPAN	Professeur des universités, Université Paris-Saclay
	Jean-Rémy CHARDONNET	Maître de conférences HDR, Institut Arts et Métiers de Chalon-sur-Saône
Directeur de recherches doctorales :	Guillaume MOREAU	Professeur des universités, IMT Atlantique Brest
Co-enc. de recherches doctorales :	Jean-Marie NORMAND	Maître de conférences HDR, École Centrale de Nantes
Co-enc. de recherches doctorales :	Camille JEUNET-KELWAY	Chargée de recherche CNRS, Université de Bordeaux

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1PP first-person perspective	23
3PP third-person perspective	viii
AoA alterations of agency	76
CBT cognitive behavioural therapy	9
CSP common spatial pattern	89
ECG electrocardiography	41
EEG electroencephalography	10
ERP event-related potential	78
fMRI functional magnetic resonance imaging	27
FoA feeling of agency	18
GSR galvanic skin response	10
HMD head-mounted display	3
ICA independent component analysis	92

IPC internal, powerful others and chance	83
JoA judgement of agency	18
LDA linear discriminant analysis	89
LoC locus of control	83
PPC posterior parietal cortex	84
RHI Rubber Hand Illusion	19
SoA sense of agency	11
SoBO sense of body ownership	11
SoE sense of embodiment	1
SoSL sense of self-location	11
SMA supplementary motor area	84
VEmb virtual embodiment	12
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VR virtual reality	1

INTRODUCTION

This thesis entitled “**Evaluation and Manipulation of Virtual Embodiment**” investigates the feeling of having a body in virtual reality (VR). To better understand this feeling, the focus will be on the evaluation and the manipulation of it in designed experiments.

The Sense of Embodiment

“Our body may be the object we know the best” states de Vignemont [Vig11]. We act with it everyday, we get sensory information constantly. Yet, what is phenomenologically to have a body? In healthy condition, we usually do not question this feeling in everyday life. We just “perceive it from the inside” [Vig11]. This feeling is called the sense of embodiment (SoE) and is defined this way by Blanke et al. [BM09]:

Sense of Embodiment

The sense of embodiment is “the subjective experience of using and having a body.” [BM09]

The next section explains why this feeling is important to study.

Motivation and Background

A better understanding of the SoE, in addition to learning more about self- and bodily consciousness, would allow a number of applications. Indeed, assessing and manipulating the SoE could help people feel embodied:

- in real life (for people with disorders such as somatoparaphrenia¹ [VR09], deper-

1. Somatoparaphrenia is a a delusion in which the person believes they don't own a body part or an entire side of their body

sonalisation² [Sie+05] or body integrity identity disorder³ [FF12]), to better study disorders and thus better treat them. For instance, in the case of depersonalisation, people have a diminished sense of self and have an altered SoE toward their own body [FS09];

- in a simulated environment (simulating reality) for a better immersion and realism.

The SoE is not easily manipulated in everyday life: we can not instantly change our point of view and see ourselves in the third person nor can we change our body or the consequences of our actions. However, these things can easily be achieved with technology, with the help of virtual reality.

Virtual Reality

Virtual reality has many definitions [AFT03]. A technical one is from Arnaldi et al. [AFT03]:

Virtual Reality

“Virtual Reality is a technical and scientific area making use of computer science and behavioral interfaces in order to simulate the behavior of **3D entities** in a **virtual world** that **interact** in real time among themselves and with the user in pseudo-natural immersion through **sensory-motor channels**.” [AFT03]

This definition brings important notions of VR:

- **Virtual world**: also called a VE, it can represent anything from a realistic reproduction of reality to a completely imaginary world following its own rules (see Figure 1). This is where users will find themselves.
- **3D entities**: composed of 3D-objects of the environment and virtual agents. Virtual agents are computer-generated characters that can engage in interactions with a user [Gui+20] and can act in the VE.
- **Interaction**: more than a simple 3D animation, and just like a video game, the user can interact with the VE, and thus change the state of this environment: open

2. Depersonalisation is a sense of loss of self, in which an individual has no control over the situation [SB01].

3. Body integrity identity disorder is a disorder characterised by an intense desire to have a physical or sensory disability [BHD12].

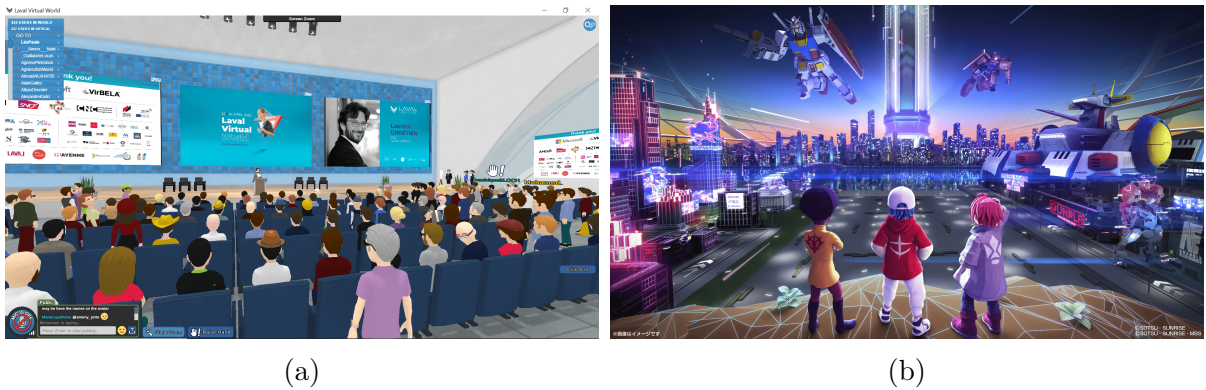


Figure 1 – (a) Virtual environment used in the virtual Laval Virtual conference, allowing multiple people to take part of this conference from anywhere. Screenshot from blog.laval-virtual.com. (b) Virtual environment of the Gundam Metaverse based on the Japanese military fiction media franchise. Screenshot from daily-vr.com.

a door, lift or push an object, make a sign to a virtual agent who can respond in turn with a sign, etc.

- **Sensory-motor channels:** VR differs from a traditional desktop video game in that it involves part or all of the user’s body (in addition to using controllers), for the motor part. But it can also include all the senses, by displaying images and playing sounds to the user. Whatever the way, it provides **feedback** to the user.

To understand how the SoE can be manipulated in VR, we will first have an overview of how VR and VEs are generated and experienced.

Devices for Experiencing a Virtual Environment

Humans know how to immerse themselves in imaginary worlds, reading a novel (or watching a movie, listening to music or simply dreaming – day or night) can project us into another universe, meet fictional characters and sympathise with them. It is also possible to use a computer screen in conjunction with a keyboard and mouse to find ourselves in a virtual world (video games or worlds simulators). Other methods have emerged with the development of VR devices: CAVE systems and head-mounted displays (HMDs)⁴.

The Cave Automated Virtual Environment or CAVE is a room-based VR system [Muh15], invented in 1992 [Cru+92]. A CAVE is a cubic room (used as an approximation of a sphere), usually $27m^3$, with several screens as walls, on which the virtual environment

4. There is a whole taxonomy of VR systems defined by Muhanna et al. [Muh15], but for clarity and simplicity, we focus on CAVE and HMDs which are the two main used systems.



Figure 2 – (a) Example of a CAVE named Immersia located in Rennes, France. (b) Example of a HMD use case. The user is an astronaut training in VR to extinguish a fire inside a lunar habitat. By ESA, CC BY-SA IGO 3.0.

is projected (see Figure 2). The side walls are made up of rear-projection screens and the floor is made of a down or rear-projection screen [Muh15]. Some CAVE systems also include a ceiling. The user is inside this room and only wears handheld wands and a special pair of goggles to get a stereoscopic view. Each couple of images projected on the screens overlaps in order to create this 3D effect. Compared to a screen, the user is in the middle of the virtual world, can move with his own body and turn his head to the right or left.

In an HMD, the screens are located in front of the participant’s eyes, and the headset is worn like glasses. Unlike CAVE, where you are surrounded by the virtual environment, using an HMD completely blocks the user’s view of the real world (including their real body) and presents them with only the virtual world. With the help of trackers, the orientation and position of the user’s head follows the user’s movements.

There are also controllers (also with trackers) that allow more interaction with the VE. In a CAVE, the space is quite large and already defined. But with an HMD, you can use it “almost” anywhere indoors, provided you have enough space. In a small space, it will be difficult to really move around. Depending on the application, the controllers can be used to teleport oneself within the virtual environment, or to move the viewpoint without physically moving. There are also other methods such as physically walking-in-place (while moving in the VE) [LAH18] or a non-linear mapping of the physical space to the virtual space (for instance participants go straight in the VE but in the physical

space go around in circles) [FLS22].

These devices allow to create more immersion, through the feeling of presence, the illusion of being there. The next section details this feeling.

Presence and Immersion in a Virtual Environment

We have seen a technical definition of VR as well as different ways of being immersed in an VE. We have also seen that the user can have the sensation of being present in a virtual environment.

In the context of this thesis, I particularly like this other definition of VR by Slater [Sla09].

Virtual Reality

Virtual Reality is “a medium in which people respond with their whole bodies, treating what they perceive as real.” [Sla09]

People **treat what they perceive as real**. Looking back at virtual therapy presented previously, we wondered if it felt like real life in VR and how VR generates those feelings. We have already mentioned the keyword of **presence**, the illusion of being there, in the VE. Another important notion is the notion of **immersion**. These two concepts are explored in this section.

Presence Presence is the illusion of being there, in the VE. Slater [Sla09] explored the question as to why participants can respond realistically to situations and events in a VE. He proposes two orthogonal components that contribute to this phenomenon: the **place illusion** and the **plausibility illusion**. The place illusion is none other than presence, the sensation of being there. The plausibility illusion, on the other hand, refers to the illusion that the scenario taking place in front of the user in the virtual world is really happening.

Immersion In terms of psychology, “immersion refers to being completely involved in something while in action. In other words, it is a state in which a participant becomes attracted and involved in a virtual space of an activity to an extension that his or her mind is separated from the physical space he or she is being active in” [Muh15]. More

technically, in the context of VR, immersion refers to the objective level of sensory fidelity a VR system provides. According to Slater [Sla09], an ideal immersive VR system not only includes a visual display but also an auditory, haptic, and tracking system. Thus, several parameters determine the quality of the user’s experience in VR, including the quality of the images, the extent of the tracking system and its latency, the range of sound and tactile stimuli, etc. The more of these parameters a VR system contains, the more immersive it will be.

Thus, VR allows us to find ourselves in a virtual world and to achieve a certain degree of immersion, which is constantly being extended by technological progress. More than that, VR allows us to go beyond what is real [SS16]. Jaron Lanier, one of the pioneers of VR who popularised the term “virtual reality”, described these differences between the real and virtual world:

Differences between the real and the virtual world

“However real the physical world is – which we never can really know – the virtual world is exactly as real, and achieves the same status. But at the same time it also has this infinity of possibility that you don’t have in the physical world: in the physical world, you can’t suddenly turn this building into a tulip; it’s just impossible. But in the virtual world you can...” - Jaron Lanier [Con+89]

In French, the term “réalité virtuelle” is often understood as a simulation of reality with the juxtaposition of the words “réalité” and “virtuelle”, which is not exactly the case in English as mentioned by Fuchs and Moreau [FMB06]. Indeed, we must not forget that VR refers to a reality that is close to, but different from, reality. Nevertheless, as Slater states [SS16], VR still operates in the space “just below [reality] what might be called the *reality horizon*“. Just like we have a body in real life, it is also possible in VR to embody a virtual body.

Interaction in VR: Avatars

Jaron Lanier said: “[Virtual reality] gives us this sense of being able to be who we are without limitation; for our imagination to become objective and shared with other people” [Con+89]. This phenomenon is referred to as virtual embodiment, defined by Spanglang et al. [Spa+14] as:

Virtual Embodiment

Virtual Embodiment is “the physical process that employs VR hardware and software to substitute a person’s body with a virtual one.” [Spa+14]

Virtual bodies are also called “avatars”. The term avatar, originally Sanskrit and associated with the avatars of Vishnu, appeared in the digital context in the 1990s through novels and massively multiplayer online games [Geo12]. Unlike the 3D entities called virtual agents mentioned earlier, the avatar is controlled by a human subject. Sherman and Craig define an avatar this way:

Avatar

An avatar is “a virtual object used to represent a participant or physical object in a virtual world; the (typically visual) representation may take any form.” [SC03]

An avatar can have any appearance: a high quality and faithful reproduction of the user, a fantasy character or even an abstract representation of a body (see Figure 3). Note that the avatar does not necessarily represent a whole body and could be for example just two flying hands that the user controls. Moreover, the avatar does not have to look like the user, it can be taller or shorter, fatter or thinner, have a different skin colour, etc.

In the context of VR, it has also been shown that using an avatar bring benefits. Several experiments showed that using an avatar improves the performance of users in cognitive tasks [PS19] and reduces cognitive load [Ste+16]. In another experiment, Lugin et al. [LLL15a] observed that having an avatar resulted in higher performance in virtual fitness training compared to having no avatar representation. Moreover, Slater et al. [Sla09; Sla+10] have shown that using embodied avatars can lead to increases of the subjective sense of presence inside VR, increasing both the place illusion and the plausibility illusion.

Applications of VR

VR is used in many areas in which avatars can be used such as entertainment [Zyd05; ASK20], learning and interactive training [Bou+15; Cla+14], medicine [Lin20] or scientific

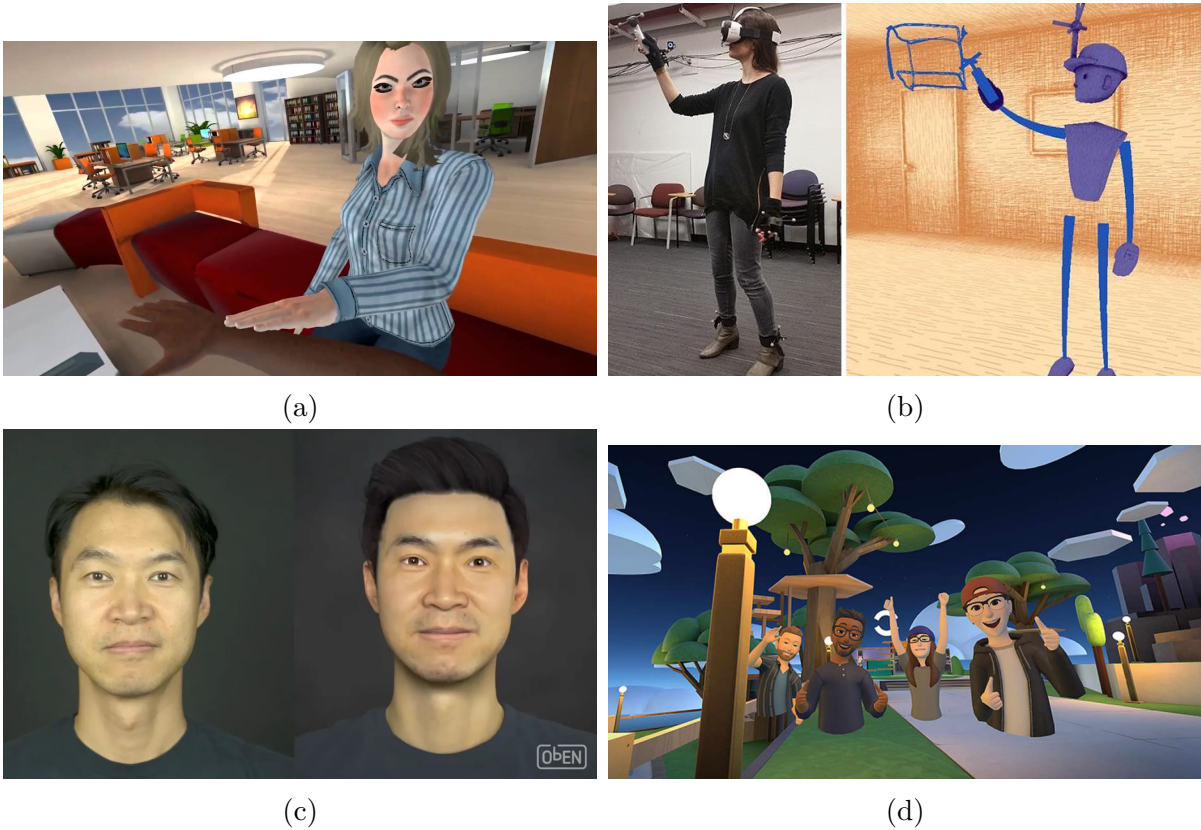


Figure 3 – Different types of avatars used in VR. (a) Avatar from beingavatar project; (b) Abstract stick-man avatar (Ken Perlin’s Holojam virtual reality system, photography by Sebastian Herscher, Holojam Artwork by David Lobser); (c) ObEN co-founder Adam Zheng and his photorealistic avatar; (d) Cartoon avatars (not full body) in Facebook’s Horizon World (picture from Meta).

visualisation [Dwy+18; Cha+15]. It has the benefit of being most of the time cheaper than real case scenario. In the medical domain, some applications are surgeries with force-feedback, for therapies or reduce the feeling of pain [Pou+18]. In the case of learning and training, VR brings security and allows to simulate particular and concrete scenarios. More generally, VR allows to better understand for a better decision making [BV17a].

Training

Training of workers can be challenging: it requires equipment, dedicated space, managers to supervise the whole training and also teams dedicated to create training scenarios. Some scenarios could not be easily accessible, like a mechanical failure, a fire or a medical emergency. It can also be hard for supervisors to clearly evaluate the performance of the trainees, except with the time required to perform a task. To tackle these issues, educational institutions and industries are moving to VR as a training tool [Car17]. It has been shown that the knowledge got from the VR training transfers to the real world [WHK98]. When using avatars, the training is more efficient [HH16] and improving the SoE would improve the overall experience and effectiveness of virtual training.

Product Design

VR is also useful for engineering and product design, ranging from 3D modelling directly in the virtual environment, prototyping and testing of products by simulating possible scenarios [Ye+07; BB20; BV17b]. Beyond functional and technical aspects, design phases also contain an emotional dimension [BB20]. In this kind of application, the SoE in VR could play a role in the overall experience [KMF09]. More generally, ergonomics issues are important in product design and a better SoE in VR could enhance the design phase.

Therapies

Psychosomatic disorders can be treated through medication or therapies, such as cognitive behavioural therapies (CBTs). CBTs have a very broad field of application: they allow the treatment of a large number of psychosomatic disorders such as addictions [Dut+08], psychoses [LL03], depressions [Cui+10], phobias [GCM01], anxiety [TP14; Car+18] and post-traumatic stress disorder [Car+18]. Generally, CBT rely on the principle of two traditional exposures: *in vivo* exposure and *imaginal* exposure. *In vivo* exposure

leads the patient to face a feared object, situation or activity in real life (for instance showing a spider to a patient with arachnophobia). However, this has some caveats: this exposure is more complicated when the fear depends on a complex context (for instance, fear of flying) or is intangible or uncontrollable (fear of being sick – nosophobia). In these cases, it is possible to use instead *imaginal* exposure, where the patient is encouraged to imagine the feared object, situation or activity. However, this greatly depends on the ability of the patient to imagine realistic mental images that efficiently trigger the fear. Indeed, it has been shown that normal aging negatively impacts the ability to imagine [Gre+15], and that clear/detailed mental images easily trigger emotions compared to unclear mental images [HM10]. These limitations can be overcome through VR exposure, the so-called *in virtuo* exposure. VR allows patients to be confronted with any situation, even ones that are not possible in real-life, intangible or uncontrollable. This alleviates users to use *imaginal* exposure and lets them focus on the virtual environment: this triggers more easily and quickly emotions, which are known to be essential for an efficient exposure process [FK86]. Moreover, VR enables modulating the degree of exposure, which is harder to do with *in vivo* exposure. For instance, in the case of arachnophobia, not only is it possible to modify the type of spider shown, its size or the number of spiders, but it is also possible to change their behaviour as needed. This also reduces the dropout rate because of unsupportable anxiety [BOU+03; WSB09]. VR also allows staying in the therapist’s office (like *imaginal* exposure), which is not always the case for *in vivo* exposure. Finally, therapies in VR are as effective as conventional CBTs compared to a waiting list control group [WSB09; Don+19; Lin20].

Evaluation and Manipulation of the SoE in VR

Evaluating the SoE is challenging because it is a subjective feeling, also defined in philosophy as a *qualia* (the subjective content of the experience of a mental state). Currently, the consensus for the evaluation of the SoE is to use standardised questionnaires [KGS12; GP18]. The advantage of these questionnaires is their ease of use. However, they also suffer from drawbacks: questionnaires can only be completed retrospectively and not continuously, and this forces the user to perform an additional task. In addition, the interpretation of the questions can be subject to variance within and between subjects [Sla04].

Other so-called quantitative measures have also emerged using physiological signals, such as galvanic skin response (GSR) — biological electrical activity recorded on the surface of the skin — or neurophysiological signals such as electroencephalography (EEG)

— measurement of the electrical activity of the brain using electrodes. The advantages of these measurements are that they do not actively involve the user and can be performed throughout an experiment. However, these measurements also have their disadvantages. Whether it be physiological or neurophysiological measures, they are subject to noise sensitivity and often need a reference value. The main drawback of physiological measures is their lack of specificity. Indeed, modulations of heart rate or GSR can be due to alterations of the SoE, but also to other internal or external factors such as the circadian rhythm or modulations of room temperature, respectively. Finally, the simultaneous use of an EEG headset and a VR headset is also complicated. This is why questionnaires remain predominant today [TM19; GP18; Jeu+18; AFL19].

Scope and Research Questions

In the scope of this thesis, we focus on avatars in the context of immersive VR using HMD-based systems. User embody an avatar that allows them to interact with the VE in which they are located and can have the impression that the avatar is their own body [KGS12].

In addition to the VR applications mentioned, the study of the SoE is important for better understanding cognitive processes (and vice versa). In order to understand and know how to measure the SoE we need to deepen our knowledge of the brain and more broadly of the neurophysiological correlates of the SoE. Despite existing measures of the SoE, there is still no reliable measure that is also quantitative. Thus, one project of this thesis consists in designing and setting up experimental studies in VR in order to better understand the SoE and to evaluate and characterise neurophysiological markers of the SoE. We will propose an interdisciplinary approach, mixing both knowledge in VR and knowledge in brain-computer interfaces/neurosciences.

The SoE is commonly characterised by three sub-components [KGS12] defined as follows. The sense of agency (SoA) is the feeling of being the cause of our actions. The sense of body ownership (SoBO) is the self-attribution of a body. Finally, the sense of self-location (SoSL) is the “spatial experience of being inside a body” [KGS12]. However, the relationships and interactions between these three components still remain unclear, especially in a VR context [KGS12]. Being able to manipulate and measure the SoE (and each components) in a reliable way allows to carry out more fundamental studies which could result in better knowledge on the brain’s functioning, notably in the context of

certain pathologies such as dissociative disorders where the relationship with the body is altered. One way to measure the SoE is to evaluate each of its components and in this way we need to be able to manipulate each component in experimental studies.

Finally, our work focuses on two research questions:

Q1 What is the interaction between the three components of the sense of embodiment?

More particularly, we will be interested in the independent manipulation of each component in an experimental setting. Indeed, being able to isolate these components would make easier experimental protocols and designs.

Q2 Are there neurophysiological markers of each component of the SoE that can be measured in real-time in a VR use case scenario?

Once experimental studies are set and neurophysiological markers can be measured, we still need a real-time measure for VR applications.

The outline of this thesis will be as follows:

Chapter 1: Related Work on Virtual Embodiment and its Evaluation Methods in VR

The first chapter dives into the literature of Virtual Embodiment and its evaluation methods in VR. A first part goes into detail on the context of this thesis, reviewing the literature about the SoE and virtual embodiment (VEmb), exploring what has been done to answer **Q1** and **Q2**. In the second part, we review the existing evaluation methods of VEmb in the literature.

Chapter 2: Study of the Relationship Between the Sub-components of the Sense of Embodiment

The second chapter presents the first experiment of this thesis and tries to answer **Q1**. We designed a within-subject experiment where 47 right-handed participants had to perform movements of their right-hand under different experimental conditions impacting the SoE: impacting the control of the avatar with visual biased feedback, modifying the realism of the virtual right hand (anthropomorphic cartoon hand or non-anthropomorphic stick “fingers”) and change the user’s point of view (first or third person). After each trial, participants rated their level of SoE.

Chapter 3: Neurophysiological Markers of the Sense of Agency

The third chapter presents the second contribution of this thesis and focus on the SoA

in order to answer part of **Q2**. In the same way as assessing each component independently is more relevant than trying to measure the SoE in VR directly, it is more relevant to look for neurophysiological markers for each component separately. We focused on the SoA, as Jeunet et al. [Jeu+18] performed a VR experiment with SoA manipulation and EEG measurements. The EEG signals had not been fully analysed. This chapter is a further analysis of these data in order to try to find EEG neurophysiological markers that characterise the SoA. We also attempt to create a classification model in order to have a real-time evaluation of the SoA. These analyses allowed us to identify different EEG modulations reflecting the SoA manipulation.

Chapter 4: Conclusion

Finally, a general conclusion sums up the different contributions as well as draw future research perspectives.

Author's List of Publications

Note: authors order for publications in submission phase may change.

International Conferences

- **GUY, M.**, Jeunet, C., Moreau, G., Normand, J-M. (2022). Manipulating the Sense of Embodiment in Virtual Reality: a study of the interactions between the senses of agency, self-location and ownership. *International Conference on Artificial Reality and Telexistence, Eurographics Symposium on Virtual Environments 2022*. **(accepted – best paper award)**⁵

Journals

- **GUY, M.**, Normand, J-M., Jeunet, C., Moreau, G. (2022). A Review of Virtual Embodiment and its Evaluations. *Frontiers in Virtual Reality*. **(in review phase)**
- **GUY, M.**, Pereira, M., Enriquez-Geppert, S., Albert, L., Argelaguet, F., Lécuyer, A., Faivre, N., Moreau, G., Normand, J-M., Jeunet, C. (2022). Alterations of agency during hand movements in virtual reality affect N200 and theta activity. **(to be submitted)**

5. This publication will be extended to a journal.

RELATED WORK: A REVIEW OF VIRTUAL EMBODIMENT AND ITS EVALUATIONS

This chapter presents a review of the literature on the Sense of Embodiment and its evaluation methods in virtual reality (VR). A first part goes into detail on the context of this thesis, reviewing the literature about the sense of embodiment (SoE) and virtual embodiment (VEmb), exploring what has been done to answer the research questions we defined. In the second part, we review the existing evaluation methods of virtual embodiment (VEmb) in the literature.

1.1 Introduction

The field of VR is becoming more accessible to the public, due to technological progress, leading to many applications such as entertainment [Zyd05; ASK20], interactive training [Bou+15; Cla+14], scientific visualisation [Dwy+18; Cha+15] or virtual therapy [WSB09; Don+19; Lin20]. In most cases, virtual bodies (also referred to as avatars) are used in VEs to represent users. In this way, it is essential to understand the so-called VEmb better, that is “the physical process that employs VR hardware and software to substitute a person’s body with a virtual one” [Spa+14]. More generally, multiple communities question the SoE (“the subjective experience of using and having a body” [BM09]) in their own way [BM09; Vig11; KGS12; Lon+08]. For instance, in neuroscience, research focuses on understanding the neural correlates related to having a body and being in control (which underpins the concept of responsibility in human societies)[Hag17] while philosophy and cognitive science question the self and bodily self-consciousness [Gal00]. The term SoE will refer to the general knowledge of embodiment across the different research communities while the term VEmb will be used when focusing specifically to VR.

Modulation of VEmb through modifications of the user’s avatar has been shown to

have (at least short-term) perceptual and behavioural impact on users [YB07; KBS13; BGS13]. To better understand VEmb, relevant and reliable metrics of the phenomenon have to be defined. This is not an easy task as VEmb is a subjective feeling. Questionnaires have been widely used in the literature [PG21] but other objective methods exist such as proprioceptive drift [BC98], response to threats [AR03] or neuroimaging [Spe+11; ESP04]. In this chapter, our aim is to review the current literature about VEmb (through the use of current knowledge about the SoE) and the existing evaluation methods of this phenomenon in VR. Pros and cons of these evaluation methods are depicted. We also provide a critical analysis of the existing measures to identify the most relevant ones in the context of VR studies.

This chapter is structured as follows. Section 1.2 defines the SoE and its sub-components (with the help of the literature of other research communities), how the sub-components are linked, and how in VR, VEmb impacts users' behaviour and perception. Section 1.3 reviews the evaluation methods found in the literature to measure VEmb as well as suggestions on how to choose an evaluation method. Finally, a discussion in Section 1.4 opens on the importance of having a real-time and reliable measure of the SoE and recent discussion about the demanding effect (participants forming an interpretation of the experiment's purpose and subconsciously change their behaviour to match that interpretation [Orn09]), before concluding in Section 1.5.

1.2 Virtual Embodiment

In this section, we define the SoE, how its sub-components interact together and review perceptual and behavioural impacts of VEmb.

1.2.1 The Sense of Embodiment

In this chapter, we focus on the VR community who studies the extent to which it is possible to feel toward a virtual body the same way we do toward our biological body [KGS12]. While we usually do not question the feeling of owning our real body, except in the case of certain pathologies [HJ16], VR offers unique opportunities to manipulate this feeling in controlled environments.

Based on Kilteni et al. [KGS12] nomenclature, which is widely acknowledged in the VR community, we define the SoE as *“the ensemble of sensations that arise in conjunction*

with being inside, having and controlling a body, especially in relation to virtual reality applications”.

According to Kilteni et al. [KGS12], the SoE is characterised by three sub-components defined as follows. The SoA is the feeling of being the cause of our actions. The SoBO is the feeling that the virtual body is the source of my sensations (like my real body). Finally, the SoSL is the “*spatial experience of being inside a body*”. As detailed in Section 1.2.2, it is known that these three sub-components are not all independent from each other, but their relationship remains unclear.

Nevertheless, the definition of the SoE is still evolving and new categories are continuously being suggested for the SoE, along with new evaluation questionnaires (see subsection 1.3.1).

In the following subsections, we detail each component of the Kilteni et al. [KGS12]’s definition of the SoE.

The Sense of Agency

The SoA is defined (across the different communities) by statements like “*I am the one in control of my actions*” or “*this is me who opened the door*” [Bra+18]. According to Gallagher, it is “*the sense that I am the one who is causing or generating an action*” [Gal00]. While this is related to the generation of an action, it is also linked to the outcome of the action in the environment, as Haggard and Chambon word it: “*the experience of controlling one’s own actions, and, through them, events in the outside world*” [HC12]. One may for instance press a button to call an elevator, which will open the door, and in this way one may feel agent toward this action. Not only one transform the environment with their action, but also experience how one changed it. Kilteni et al. [KGS12] follow the definition of Blanke and Metzinger where the SoA refers to the sense of having “*global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will*” [BM09].

The most commonly used theory to explain the SoA at a cognitive level is the **comparator model** (also called the **central monitoring theory**) [BWF98; Fri92; DNV08]. An action starts with an intention, followed by a prediction of the outcome of the motor command. Then, the motor command is performed, which gives a sensory feedback. Finally, the prediction is compared with the outcome to compute a prediction error. This prediction error allows three things: (a) to adjust the current motor command; (b) to attribute agency toward the actions made (if the prediction error is null) and (c) to alleviate

the sensations made by our own actions, which are predictable (see Figure 1.1).

However, this model has some limitations: when there is no prediction error (i.e. in successful actions), this model fails to explain the feeling of agency [Hag17]. Indeed, it has been shown that even distorted action outcomes can be experienced as self-produced [Far+03]. Moreover, it can happen that people attribute the same distorted feedback to their actions and sometimes to someone else’s actions [Far+03; SVN08], which is not explained by the comparator model.

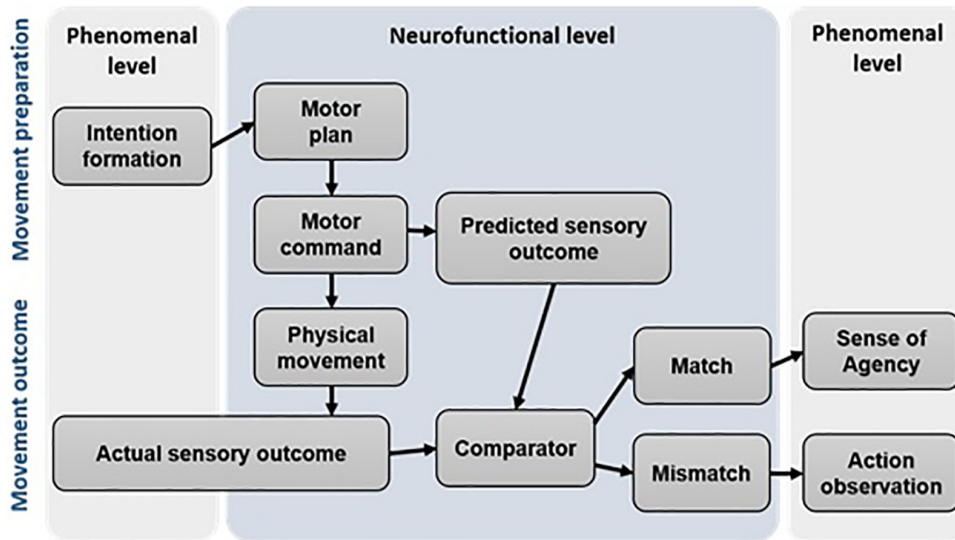


Figure 1.1 – Blakemore’s and Frith’s comparator model (also called the central monitoring theory) explaining the SoA. An action’s outcome is matched with a predicted outcome to attribute agency (Figure from [Bra+18]).

To account for these limitations, Synofzik et al. [SVN08] suggested an extension that not only takes into account the retrospective aspect of agency (inferring agency after the outcome is known as explained by the comparator model) but also considers the prediction of the outcome of our actions. Indeed, the SoA is commonly separated into two components: the **feeling of agency (FoA)** and the **judgement of agency (JoA)** [FF02; SVN08; Gal12].

The FoA relates to the intent to act. It is pre-reflective, implicit, low-level and non-conceptual. The FoA starts at early stages of the action, before the perception of the feedback.

On the contrary, the JoA relates to the result of an action and occurs when we explicitly attribute agency to the self or other. It is reflective, explicit, high-order and conceptual. The JoA is computed once the feedback has been perceived and processed [SVN08]. The

retrospective account of the SoA relies on 3 principles [WW99]: the priority principle, the consistency principle and the exclusivity principle. The priority principle states that the thought should precede the action at a proper interval. According to the consistency principle, the thought should be coherent with the action. That is, the sensory outcome should match the predicted outcome. Finally, the exclusivity principle states that the thought should be the only apparent cause of action. In other words, there should not be any outside influence in the outcome.

In VR, the SoA is present when interacting with the VE. Indeed, the way users control their avatars changes the way they can interact with the VE, and thus their level of immersion and their SoA [Sla09]. The experience will not be the same when using controllers to teleport their avatar or using full-body tracking to move themselves. For instance, Eubanks et al. [Eub+21] found that having foot tracking significantly improves the SoA and the SoSL compared to Head-and-Hands tracking or no tracking at all. Moreover in their experiment, Waltemate et al. [Wal+16] observed that motor performance is affected by latency (induced by signal transmission and processing of tracking) when it is above 75ms, and it also impacted negatively the SoA when the latency is higher than 125ms. This echoes the priority principle defined by Wegner et al. [WW99], according to which the JoA is impacted if the action is too much delayed from the thought of the action.

The Sense of Body-Ownership

The SoBO is defined by statements like “*this is my body*” or “*I am the one who is having this feeling*” [Bra+18]. SoBO is, as Gallagher defines it, “*one’s self attribution of a body*” [Gal00]. This is the definition that Kilteni et al. [KGS12] and the VR community commonly follow. In some communities we refer to the more general Sense of Ownership which relates to ownership toward a body part (as opposed to the whole body) [Bra+18]. However, in VR the distinction is not always made and mostly refer to the SoBO. Indeed, in the context of VEmb, we primarily focus on full-body avatars, and thus want to focus on the link between the self and the full body. In the following, we will use the term SoBO even when just a body part is studied. For a detailed review of the Sense of Ownership, see [Bra+18].

Many disciplines have investigated the conditions required for a SoBO to emerge, among which are phenomenology, philosophy of mind and cognitive science [Bra+18; Tsa10; Vig11]. With the Rubber Hand Illusion (RHI) [BC98], Botvinick and Cohen have shown that by stroking synchronously the (hidden) participant’s real hand and a rubber

hand, an ownership illusion toward the rubber hand could be elicited. Each participant had their arm on a table, hidden behind an opaque screen, and a real-sized rubber hand is placed in front of them (see Figure 1.2). They were asked to look at the rubber hand while the experimenter brushed the real hand and the rubber hand. The experiment had two experimental conditions: the brush strokes on the real and virtual hands were either synchronous or asynchronous. The synchronous tactile stimulations resulted in participants having the feeling that the rubber hand was their own hand, which was not the case for the asynchronous tactile stimulations. Moreover, participants felt that their real hand “drifted” toward the rubber hand (see section 1.3.2). The RHI has been later expanded to VR [Len+07], and generalised to full-body illusions [Sla+09]. Some studies questioned if it was possible to induce a SoBO toward non-hand objects. Armel and Ramachandran [AR03] managed to reproduce the RHI toward the surface of a table, but the SoBO was reported to be lower than with the classical RHI. Several studies were led afterwards but could not replicate that specific result [TH05; Tsa08; Tsa10]. A SoBO could also be elicited toward non-hand virtual objects, but only if a SoBO toward a virtual hand was first elicited, explained by bottom-up influences (see below) [HP10].

To summarise, the SoBO seems to emerge from two processes: bottom-up influences (sensory information) and top-down influences (cognitive processes assuming an internal body map) [Tsa10; TH05].

Bottom-up influences Bottom-up influences refer to the afferent sensory information from one’s sensory organs, such as visual, tactile and proprioceptive inputs (the feeling of body position and movement [TA18]). According to the Bayesian perceptual learning theory [Hat90; AR03], the brain infers hidden causes from sensory signals (e.g., hearing a dog barking implies the existence of a dog [Kil+15]). The RHI and more generally the sense of ownership might work by merging the touch on the location of the rubber hand and the feeling of the touch on the real hand [AR03]. Indeed, in an RHI experiment, Armel and Ramachandran [AR03] measured the GSR with either a rubber hand or just a table. They observed that the illusion of ownership is significantly lower when the real hand is simultaneously visible during stroking, suggesting that the illusion is due to a spatio-temporal correlations between visual and tactile information. Thus, any object could be experienced as part of one’s body. Finally, Armel and Ramachandran [AR03] state that a visuotactile stimulus is necessary and sufficient to induce the RHI.

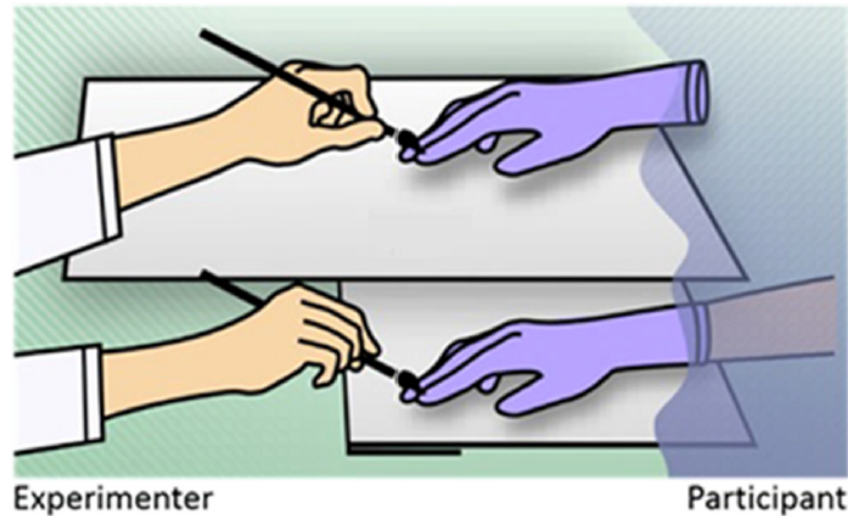


Figure 1.2 – The classical rubber hand illusion as originally introduced by Botvinick and Cohen [BC98]. The two hands (the participant’s real hand, hidden from view, and a rubber hand, visible by the participant) are stroked synchronously by the experimenter. Figure from [Bra+18].

Top-down influences Top-down influences refer to all the cognitive processes linked to the treatment of sensory signals and stimulations. The main top-down explanation of the SoBO is the neurocognitive model of SoBO, in which the SoBO is based on pre-existing internal body maps and is integrated from different information sources [Tsa10]. This neurocognitive model is a comparator model of the SoBO working with three levels: the first level opposes the visual appearance of an observed object to a pre-existing, temporally stable body model; on the second level, the current body schema state is compared to the anatomical, structural, and postural features of the observed object; finally the different sensory information about the observed object are matched in the third level, to give rise to a SoBO if coherent. This neurocognitive model processes each level successively. If there are enough similarities, the second level is processed, until the third and last level. Regarding the top-down effects in experiments, it has been shown for instance that in order to induce ownership toward an external object, a basic morphological similarity with the real body part (or whole body) is needed [AR03; Tsa+10; TH05].

As of now, it is unclear how these two processes (bottom-up and top-down influences) interact. As stated by Braun et al. [Bra+18], while there is a general agreement that our somatosensory input processing is structured by at least some internal body maps, the weight of top-down modulation remains unclear. Slater et al. [Sla+10] show in a VR

experiment that bottom-up perceptual mechanisms can momentarily override top-down knowledge by altering the sense of one’s body with an illusion of temporary transformation in form and size of the body.

The SoBO is influenced by the avatar representation [LLL15a; LLL15b]. Indeed, in VR, the avatar can represent anything from a realistic human [Lat+17] to a less realistic but human-like/anthropomorphic avatar [LLL15a; LLL15b], or even to non-human avatars [Ahn+16; SGF22]. The avatar can vary in height, shape, colour or rendering style (e.g. cartoon or photo-realistic). In their experiment, Lugin et al. [LLL15a] observed that having an avatar resulted in higher SoBO (in a virtual fitness training setup) compared to having no avatar representation (similar results were found in [Eub+21]). In another work [LLL15b], Lugin et al. showed that it is possible to experience a SoBO with full-body avatars with different degrees of anthropomorphism (a block-man, a robot or a human avatar). They observed that there could be an uncanny valley effect [Mor12] when using human avatars. The authors explain it as a drop in acceptance for those avatars due to subtle imperfections of appearance. Avatars can also be personalised to fit the users’ real appearance (for instance with 3D scans). Waltemate et al. [Wal+18] have shown that personalised avatars (individualised 3D-scanned versions of participants) significantly increase the SoBO, presence and dominance (the perceived state of own social dominance or submission). They also used individualised 3D scanned models of participants, which increased the SoBO. Finally, it appears that the closer an avatar is to the user’s real appearance, the better it is for the experienced SoE [Wal+18]. The avatar’s realism should thus be increased to maximise the SoBO but one should be careful with the possible uncanny valley effect.

The Sense of Self-Location

According to Kilteni et al., self-location “*is a determinate volume in space where one feels to be located*” [KGS12]. This volume in space is normally localised within the physical body [BM09], but can be altered in situations of out-of-body experiences [Ehr07]. The SoSL refers to the spatial experience of being inside a **body** [KGS12]. Note that it is different than the experience of being inside a virtual world (which can happen also without a body or avatar) which relates to the presence – the sense of “*being there*” – or the Place Illusion [Sla09]. While similar and complementary concepts, the SoSL relates to the body while presence relates to the virtual world. This is why presence is left out of this chapter, as we focus on the relationship between the self and the body in VR (for a review

of presence see for example the work of Felton and Jackson [FJ22]). The main question in this section is then, as written by Lenggenhager et al. [LMB09]: “*Do we localise ourself according to where we feel our body to be (somatosensory cues), where we see our body to be (visual cues) or at the origin of our visual perspective?*”. Interestingly, it has been found that it is possible to feel localised at two different places at the same time [Wis+11]. It appears that the SoSL is based on 3 aspects: the visuospatial perspective, vestibular signals, and tactile inputs [KGS12].

The visuospatial perspective relates to the user’s point of view, being a first-person perspective (1PP) or a 3PP (see Figure 1.3). This aspect is important as, apart from pathological conditions, one feels consistently in a 1PP. It has been shown that modifying the origin of the visual perspective (which is easily done in VR experiments) impacts the place where one feels located, i.e. the SoSL [BM09; Ehr+07; Len+07; LMB09]. Moreover, when the virtual body is exposed to a threat (see section 1.3.2 for details about threats and self-location), physiological changes have been observed, and those changes are greater in a 1PP compared to a 3PP [AR03; PE08; PKE11].

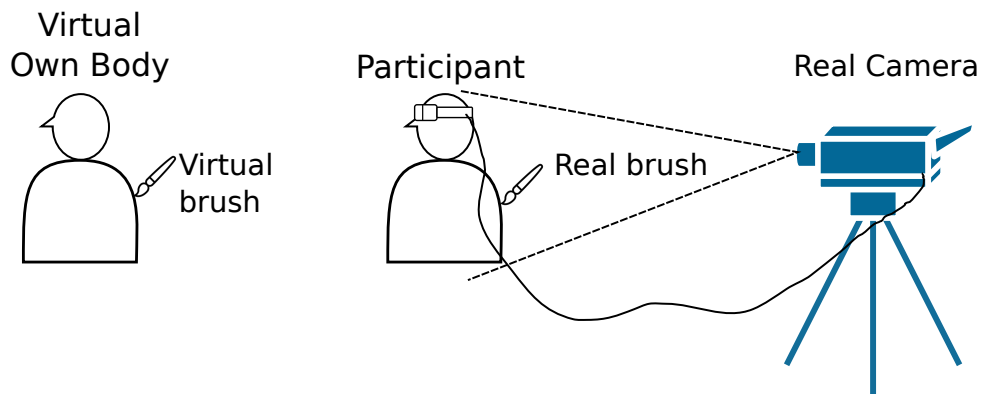


Figure 1.3 – Third-person perspective embodiment induced by visuo-tactile stimulations. This is one possible way to achieve 3PP in a “real” environment, note that in fully-digital VE it is much easier to achieve such a perspective change by modifying the position of the virtual camera. Inspired from [Len+07].

Vestibular signals also play an important role in the SoSL [LHB08]. They consist of body information of rotation and translation, as well as orientation in relation to gravity [BM09]. It appears that patients who have experienced out-of-body experiences (i.e., the feeling to be outside of their body with the visual perspective also coming from outside the body boundaries) had a vestibular dysfunction [KGS12; Bla+04].

Finally, tactile stimulations are linked to proxemics and surroundings. The former split

up in three categories [Hal+03]: (1) personal space which is limited by the skin; (2) peripersonal space which is everything at grasping range (reported at $45 \pm 7\text{cm}$ in [Rab+20]); and (3) extrapersonal space which is all that is out of reach. This is linked to the way the brain encodes the surrounding space relatively to the body. Studies have shown that the SoSL can indeed be manipulated by synchronous visuo-tactile stimulations. For instance, Normand et al. [Nor+11] embodied participants in avatars with body volumes different than their real biological body, which resulted in a differently perceived personal space.

All three components of the SoE have been presented in isolation, reviewing their definition and factors impacting VEmb (see Table 1.1 for a summary). However, they all work together to constitute the SoE and are not independent from each other. This is detailed in the next section.

Categories	Factors	References
Avatar	appearance	[LLL15a; LLL15b; Arg+16; LJ16; Wal+18]
	control	[Wal+16; Eub+21]
	point of view	[MS13; Che+18]
User	locus of control	[Jeu+18; Dew+19]
	preference	[Fri+20]

Table 1.1 – Summary of factors that favour the SoE, split in two categories: the avatar, and the user.

1.2.2 Inter-dependency of the components of the SoE

In this section, we review the literature in order to analyse the inter-dependencies existing between the components of the SoE. Two main questions are of interest: (1) what are the relationships between the SoE and its sub-components; (2) are there any links between the sub-components?

Relationship between the SoE and its sub-components

According to Kilteni et al. [KGS12], it is yet unknown if there is a dominant component or if they all have the same weight. Some authors treated the SoSL as synonymous to VEmb [BM09; Len+07]. Some other authors have proposed that the SoBO is not essential to feel embodied [DT09]. This is motivated by experiments eliciting tool embodiment (feeling a tool to be an extension of one’s body [WP19]) in which there is no SoBO involved [Vig11]. Regarding the SoA, Tsakiris et al. [TLH10] state, based on their experiment using

fMRI and video-projected images (not in VR), that the perceived agency is an important factor, as confirmed by Newport et al. [NPP10] concluding that a lack of agency may inhibit embodiment (in a non-VR experiment).

However, to the best of our knowledge, no research has been made to exclusively study the relative importance of the three components to experience a SoE. As Kiltner et al. suggest, this may be time-varying, or even experiment-specific [Kil+12]. More recent experiments show that users' personality traits and preferences play a role in VEmb as well [Bur+19]. The locus of control (describing how people attribute the control they have over the outcome of events in their lives) has been found to impact the SoE [Jeu+18; Dew+19]. Moreover, users' preferences have been studied by Fribourg et al. [Fri+20]. In this study, participants started with a "minimal" SoE condition (minimal anthropomorphic avatar, no control – automatic animation playing – and a 3PP) and progressed toward an "optimal" SoE condition (realistic avatar, full-body motion capture and a 1PP). To do so, users increased the level of each factor in the order they wanted. The results showed that the avatar's appearance was increased last and that participants consistently preferred to increase first the level of control (from automatic animation playing to triggered animation to inverse kinematics to full-body motion capture) and the point of view. Moreover some configurations (considered as a "suboptimal" SoE) revealed an equivalent SoE as the one felt in the optimal configuration as measured with a standardised questionnaire (see subsection 1.3.1). Since potential preferences of users could vary depending on the task, the authors designed four different tasks using a full-body avatar in order to cover more widely the range of possible actions in a VE: a task involving the upper-body in which participants had to hit a punching bag; a task entailing the lower-body by hitting a soccer ball; a third task to follow fitness movement, with no interaction with the environment; and finally a walking task with obstacles to avoid.

To summarise, there is currently no consensus about the weight of each sub-component of the SoE, and we believe it remains under-studied. As concluded by Fribourg et al. [Fri+20], users tend to prefer increasing the level of control and the point of view before increasing the avatar's realism, which would give more weight to the SoA and the SoSL compared to the SoBO. Nevertheless, the dynamic and evolution of the relative importance of each sub-component remain unknown.

Interactions between the sub-components

The way the SoA, SoBO and SoSL interact with each other to form (or not) a SoE remains unclear as well. We review in the following paragraphs the literature regarding the two-way interaction between each pair of components.

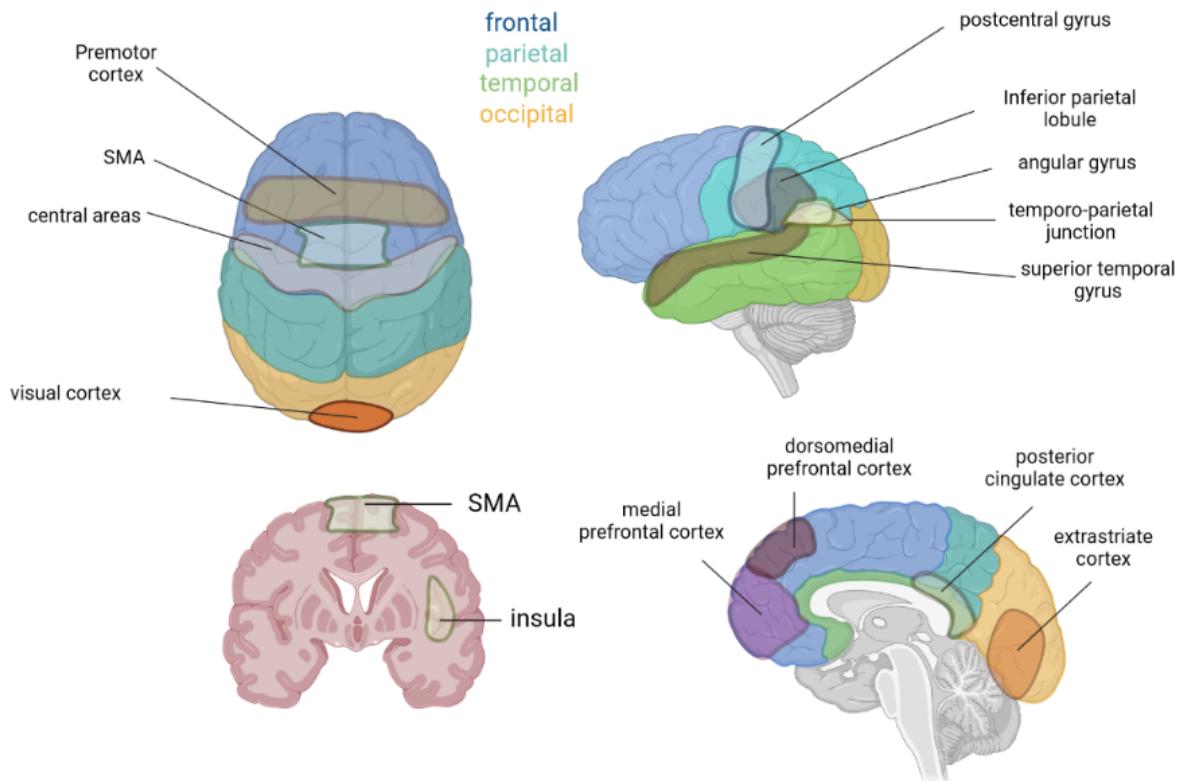


Figure 1.4 – Various brain regions mentioned in the literature regarding the SoE. Zones are approximate, for illustration purposes. (top-left) superior view of the brain; (top-right) lateral view of the brain; (bottom-left) coronal cut of the brain; (bottom-right) sagittal cut of the brain. Made with biorender.com

Interaction SoSL/SoBO As seen in section 1.2.1, the visual perspective is related to one’s SoSL. Petkova et al. [PKE11] found in a VR experiment that the visual perspective has an impact on the SoBO. It was unknown at the time if breaking the SoSL weakened the SoBO and whether the 1PP was mandatory for experimenting a SoBO. Later, in a VR experiment, Maselli and Slater [MS13] concluded that the 1PP was essential for the SoBO to occur. Nevertheless, Chen et al. [Che+18] state that a SoBO is still possible

in a 3PP in VR. In another VR experiment, Maselli and Slater [MS14] state that “*self-location and ownership can be selectively altered*” although strongly coupled. Serino et al. [Ser+13] reviewed VR and non-VR neuroimaging studies and concluded that the SoBO and the SoSL are associated with modulations of brain activity in different brain regions (respectively in the premotor cortex – involved in movement planning of proximal muscles – and in the temporo-parietal junction – electrical stimulation of this region can produce perception illusions like out-of-body experiences [BA05]; see Figure 1.4). Nevertheless, as the authors state, bodily experience is considered in isolation (that is the SoBO on one side and the SoSL on the other side) although the body interacts with objects within the peripersonal space (which mixes the SoBO and the SoSL). A multisensory representation of the peripersonal space is created by combining body-related signals with information about external stimuli existing in the vicinity of the body [GC06].

Interaction SoA/SoBO Regarding the link between SoA and SoBO, there is currently no consensus in the community. There are two models (from the neuroscience community) of the relation between the SoBO and the SoA: an additive model in which they are both strongly related [TLH10], and an independent model where the SoBO and the SoA are qualitatively different experiences, with distinct brain networks, as denoted by Tsakiris et al. [TLH10]. According to [TSG07], a SoBO does not imply a SoA but a SoA “normally” implies a SoBO. For Kalckert and Ehrsson [KE12] however, SoBO and SoA were found to be independent from each other. Tsakiris et al. [TLH10] found in a RHI-like experiment (not in VR) that the SoA is “*responsible for the coherence of body ownership*”. Indeed, sensory mechanisms used in the RHI elicit a SoBO based on a local representation of the body while the action (therefore the SoA) gives coherence of the whole bodily self representation [TLH10]. In VR this time, some factors, like the avatar’s realism, may influence the SoBO. The hand design has been found to sometimes have an impact on the SoA [Arg+16] and sometimes not [LJ16]. The relationship between these two components of the SoE may vary depending on the experimental conditions, as stated by Chen et al. [Che+18]. These authors have performed multiple RHI experiment variations (not in VR). A key difference between their experiments and other RHI experiments is that Chen et al. implemented multiple manipulations (tactile stimulation and active movement) at the same time. They argue that the SoBO “*was strengthened and extended*” by the SoA. This could explain the varying relationship between the SoBO and the SoA. Nevertheless, more recently in a meta-analysis on functional magnetic resonance imaging (fMRI) studies

only, Seghezzi et al. [SGZ19] concluded that the brain has three different regions that process the SoBO and the SoA: two regions to separately process them, and one common region to aggregate the SoBO and SoA at a higher level. The SoBO seems to be processed in the left inferior parietal lobule and the left extra-striate body area, which may be “*part of a network in which multisensory inputs are integrated*” (see Figure 1.4). In turn, the SoA seems to be processed in the left sensorimotor area, the left posterior insula, the right postcentral gyrus and the right superior temporal lobe. Finally, the SoBO and SoA are integrated in the left middle insula, having a role in sensorimotor integration [Cau+11] (see Figure 1.4). The presence of distinct but also common regions in charge of processing the SoBO and the SoA could explain the discrepancy in the results found. This may be due to some experimental protocols in which the sensorimotor integration in the left middle insula is not done. Studies should be made to further understand these processes and to compare previous experiments with different experimental protocols.

Interaction SoA/SoSL Finally, the link between the SoA and SoSL has received, to date, little attention from the VR community. In a non-VR experiment, van den Bos and Jeannerod [VJ02] presented healthy participants with an image of both their own hand and an experimenter’s hand, which could either make the same or a different movement, in various orientations. Their results showed that perspective taking (linked to the SoSL) influences the recognition of one’s action (linked to the SoA). Perspective taking in this experiment is however not exactly the SoSL as conceived in VR as defined by Kilteni et al. [KGS12] and thus these results might not apply to VR. David et al. [Dav+06] performed an fMRI study where agency and the visuospatial perspective are manipulated in a virtual ball-tossing game with 3D scenes and virtual characters on a screen. They found no significant interaction between the visuospatial perspective and the SoA. While using avatars, this experiment was however not in VR but on a screen-based desktop 3D environment, which limits the user’s experienced SoSL. Thus, the question of whether the SoSL and the SoA are dependent or not in VR remains open.

Interaction SoA/SoBO/SoSL To the best of our knowledge, there is currently no experiment studying the interaction between the three components at the same time. Nevertheless existing results tend to show that the SoA and the SoBO are partly dependent, the SoBO and the SoSL are closely related, while the link between the SoSL and the SoA remains unknown (see Figure 1.5). This dependency makes the evaluation

and measure of VEmb harder. Indeed, as we do not know how to fully assess the SoE, it is usually done by analysing separately each component. However, depending on the experimental protocol, the influence varies, and some components might be selectively altered, as stated by Maselli and Slater [MS14]. It is still unclear what factors impact this inter-dependency, and further studies should be pursued to answer these questions. Moreover, these results depend on how the SoE and its components are measured, which is reviewed in section 1.3.

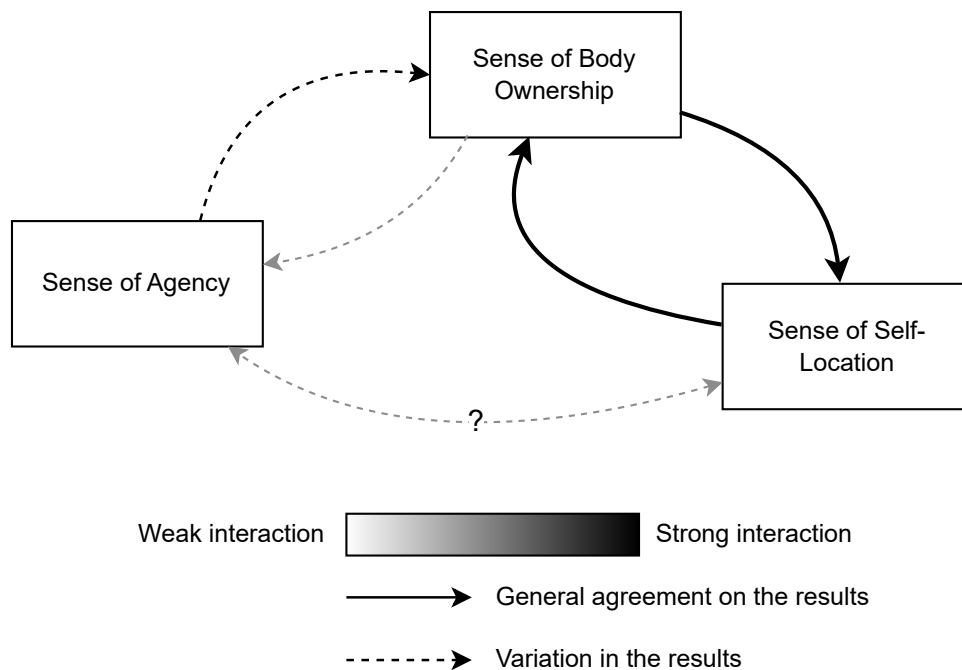


Figure 1.5 – Visualisation of the current knowledge about the inter-dependence of the different components of the SoE. The SoA and SoBO are, depending on the context, sometimes found independent and sometimes found to be linked. Moreover, it has been found that they are processed separately by two distinct brain regions, and a third region aggregate information at a higher level [SGZ19]. The link between the SoSL and the SoA remains unknown. The SoSL and SoBO are strongly linked.

1.2.3 Perceptual and behavioural impacts of Virtual Embodiment

The study of VEmb has shown that the users’ perception of their body as well as their behaviour can be modified in VR [KBS13; BGS13]. Users see themselves in the

VE through an avatar and the characteristics of this avatar can modify their perception and behaviour. This is allegedly linked to the Proteus effect stating that participants change their identity and behaviour by taking the perspective of an avatar different from them [YB07]. In the following paragraphs, we review different articles showing this effect, in different situations.

VEmb can improve performance in cognitive tasks [Ste+16; BKS18]. Indeed, Banakou et al. [BKS18] have shown that people embodied in an avatar looking like Einstein manifested an improvement of performance in cognitive tasks compared to those who were not, as if, while being Einstein, participants had to “be smart”. This improvement was higher for people with low self-esteem. Furthermore, VEmb in this experiment would reduce implicit bias toward old people (the fact of associating stereotypes to a group of people – old people – without conscious knowledge [Bro19]). It is not clear however if this implicit bias reduction is because of embodying an old person or Einstein, who is an eminent and famous old person.

In another experiment, Kilteni et al. [KBS13] embodied Caucasian people in either a “*casually dressed dark-skinned virtual body*” or in a “*formal suited light-skinned virtual body*”, where they played West-African Djembe hand drum in VR. Both groups showed a strong SoBO, however the casually dressed dark-skinned group also showed “*significant increases in their movement patterns for drumming compared to the baseline condition*”, although they were not Djembe players. It is again as if users “played a role” guided by stereotypes (without being asked to). This modification of movement increased the more a participant felt a high SoBO (reported via a post-experiment questionnaire – see subsection 1.3.1).

In [BGS13], Banakou et al. embodied adult participants in a 4-year old child or in adult virtual bodies scaled to the same height as the child, by using immersive VR in 1PP with a HMD. A SoBO could be experienced in both conditions, with similar strength, by means of visuomotor synchrony (the virtual and real body movements were synchronised). The authors observed an overestimation of the size of objects compared to a non-embodied baseline, and this overestimation is significantly greater when embodied in the child body compared to the “scaled-down” adult body. They performed a second experiment with additional participants, similar to the first one except that there was no body-ownership illusion, by visuomotor asynchrony. The overestimation found in the first experiment did not appear in this second experiment. They conclude that “*there are perceptual and probably behavioural correlates of body-ownership illusions that occur as a function of the*

type of body in which embodiment occurs” [BGS13].

However VEmb does not always have an impact on participants. Indeed, in [Ver+18], Verhulst et al. analysed shopping behaviour and the perception of different products in VR for participants embodied in an avatar with average Body Mass Index (BMI) or in an obese avatar. They expected stereotypes classically associated with obese people (called the “weight stigma”) to emerge, like unhealthy diet by buying more food products and products with high energy intake, as well as rating unhealthy food as being tastier compared to participants in normal (in the sense of the World Health Organization) BMI avatars. The results showed no modification of behaviour of participants embodied in obese avatars toward negative stereotypes nor buying healthier products, except coke as less healthy and apple as tastier. In this experiment, a product is given a “healthiness score” by computing its Nutrient Profile score based on the nutritional content of the food/drink (the lower the nutrient profile, the healthier the product is). However, these results have some limitations as the participant pool lacked diversity (all the same background and of Asian culture), and using BMI as an indicator of healthy nutrition can be challenged.

The former studies have in common that they have embodied participants in human-like avatars. However, some researchers also studied embodiment in non-human avatars. It is possible, for example, to embody in an animal or a vegetable. For instance, in [Ahn+16], Ahn et al. embodied participants in a cow or a coral in a VR experiment. Participants revealed greater connection between the self and nature when in VR as compared to watching the experience on video. Moreover, this higher interconnection with nature elicited “greater perceptions of imminence of the environmental risk and involvement with nature, which persisted for 1 week” [Ahn+16]. More recently, Spangenberg et al. [SGF22] embodied participants in a tree in an experiment using VR and desktop monitor. Whichever the medium used, a higher SoE resulted in a greater relatedness to nature (as measured by the Nature Relatedness Scale [NZ13]). The effect was not stronger for the VR condition, suggesting that VR does not improve nature relatedness. However, participants reported to be more immersed in VR which “*provoked reflective processes on one’s role towards nature*” more than with the desktop.

In the previous paragraphs, we observed that VEmb has many impacts on the behaviour and perception of participants, depending on the type of avatar. It can also change implicit biases people have [Pec+13; BHS16; BKS18], up to one week after the experiment [BHS16]. Indeed, in their VR experiment, Peck et al. [Pec+13] observed that light-skinned females embodied in a dark-skinned avatar significantly reduced their im-

PLICIT racial bias against dark-skinned people. Thus, the SoE can impact the experience that users have in VR systems and these impacts should be studied as VR systems are becoming more and more accessible to the general public. Non surprisingly, to the best of our knowledge, these impacts have mostly been studied in the short-term. Nonetheless, Barberia et al. [Bar+18] conducted a VR experiment to study mortality and near death experiences, in which participants are embodied in a humanoid alien body, with two companions (which are either confederates (experimenters) or other participants). For a total of 6 sessions over successive working days, they performed different tasks and explored the VE together, starting as a child and gradually ageing. Over time, each participant witnessed the death of their companion, until their own death in the last session. While there are ethical issues to consider with VR for experimental studies [MM16], this study was designed to be pleasant and participants reported to have overall positive experiences. This experiment was designed to give a methodology to study mortality and near death experience in VR more than to study impacts on users. While embodiment was not the focus of this study, this could be used for future longer studies on embodiment.

In light of these impacts, it is important to better understand VEmb. To achieve this objective, relevant and reliable metrics of the phenomenon have to be defined. In the next section, we review the different evaluation methods of the SoE, and how the SoE is manipulated through each sub-component in VR.

1.3 Evaluation of Virtual Embodiment

In this section, we describe how VEmb has been evaluated in the literature. First, we focus on self-reported questionnaires in general. Then, we elaborate on additional evaluation methods for each sub-component of the SoE, see Table 1.2 for a summary.

1.3.1 Questionnaires

Questionnaires are the main method used to evaluate VEmb [KGS12; GP18].

In order to evaluate the ownership toward the rubber hand in the RHI, Botvinick and Cohen [BC98] asked the participants to fill-in a 9-item questionnaire (in a random order) on a 7-point Likert scale. Some questions, such as “*I felt as if the rubber hand were my hand*”, relate specifically to the SoBO toward the rubber hand. Some other questions were more general and exploratory. Note that, at the time, only the SoBO was the focus,

explaining the lack of questions regarding the SoA and SoSL. In further experiments (not necessarily in VR), new questions were added not only to evaluate the SoBO but also the SoA (e.g. “*it seemed like I was in control of the rubber hand*” [Lon+08]) and the SoSL (e.g. “*I experienced that I was located at some distance behind the visual image of myself, almost as if I was looking at someone else*” [Ehr+07]). Most, if not all, of the following experiments, inspired by the rubber hand illusion, used questionnaires to assess the SoE. They were either referring to a physical body part (for instance the rubber hand [Lon+08]) or to a virtual body part [Sla+10]. Some questions of Botvinick and Cohen’s questionnaire have been reused as is in [Ehr05; Len+07; Arg+16], some others adapted to the particular experiment [Nor+11]. Also, new questions were added, depending on the experiment, as exploratory questions [LCH08; Nor+11; DR13]. For instance, in Normand et al.’s experiment [Nor+11], they used this new question “*I felt an after-effect as if my body had become swollen*”, which makes sense in their experiment but not necessarily in other studies. This led to a lot of different questionnaires used in the literature, which makes it hard to compare results between the experiments.

To overcome this problem, many researchers intended to create standardised questionnaires by grouping the most frequent and relevant items from the literature [DR13; GP18; PG21; Eub+21]. Gonzalez-Franco and Peck [GP18], for instance, have identified 6 main categories of questions depending on the experiment: body-ownership, agency, self-location, but also motor control, tactile sensations, external appearance and response to an external stimulus. This echoes De Vignemont’s categories of measures of embodiment being spatial measures (“*is the space surrounding the embodied object processed as peripersonal space*”), motor measures (does one feels that the embodied object “*directly obeys one’s will*”) and affective measures (is the embodied object “*protected from hazardous situations*”) [Vig11]. Peck and Gonzalez-Franco [PG21] continued their work and refined this standardised questionnaire by collecting data from nine experiments with over 400 questionnaire answers. In this updated version, they removed non-universal questions or redundant questions, reducing the questionnaire from 25 to 16 items. This allowed them to reshape the different sub-components of embodiment, now named *Appearance*, *Response*, *Ownership*, and *Multi-Sensory*. Peck and Gonzalez-Franco state that this new version produces a wider range of embodiment scores compared to the older questionnaire. These categories are not the same components as the ones defined by Kilteni et al. [KGS12]. Notice how for instance there is no *Agency* sub-component in this new categorisation of embodiment. Instead, the SoA is considered a transversal factor and SoA scores can be

computed by merging questions of *Appearance*, *Ownership* and *Multi-Sensory* categories. This makes sense with the literature where for instance visual appearance of the avatar is shown to have an impact on the SoA [Arg+16; LJ16; Che+18]. Note that the categories with the same name in the 2018 and 2021 versions of Peck and Gonzalez-Franco questionnaires [GP18; PG21] are **not** identical, but previous categories are correlated to the new ones.

Although some questions still need to be adapted to a given experimental design, it is possible to do so without drastically changing them. For instance, questions about “*feeling a touch*” during the experiment can be used even if the user is not supposed to be touched, by referring to the feet touching the virtual floor. The authors of [PG21] encourage adapting the questions following their guidelines instead of removing non-applicable questions in order to provide a better comparability between experiments.

Meanwhile, Roth and Latoschik reviewed the literature in order to create their 12-item Virtual Embodiment Questionnaire (VEQ) [RL20]. They aimed to extend a previous SoBO questionnaire [Rot+17], tightly constrained to virtual mirror scenarios¹ (making it hard to adapt to other experiments, thus reducing the comparability between experiments). Roth and Latoschik state their questionnaire also needed validation, consistency and balancing in the number of items of each component. The VEQ addresses these issues by adapting the questions to generic scenarios and balancing the number of items in each category, while keeping the same categories.

The authors reviewed the literature to identify questionnaire items and performed a confirmatory factor analysis on the data from three experiments. They identified three factors: (1) ownership of a virtual body; (2) agency over a virtual body; and (3) change in the perceived body schema. Finally, they tested the questionnaire by confirming the reliability and validity of the scale. Note that there is no self-location factor. This is indeed voluntarily out of the scope of this questionnaire, as the authors argue that the main goal in VR is to be in a 1PP and not disturb the SoSL. They may address this issue in future works.

Broad use of one of these standardised questionnaire would greatly help the comparison of different experiments, and the authors of both these new questionnaires invite the community to do so. However, there are still new questionnaires arising in the domain [Eub+21], making it hard to converge toward a standardised way to measure embodi-

1. Participants look at their avatar through a virtual mirror and have to perform different tasks such as “*Look at your left hand*” [RL20]

ment via questionnaires in experiments. Eubanks et al. [Eub+21] questionnaire’s goal is to address the three factors of embodiment as defined in Kiltner et al. [KGS12], with a low amount of questions. They validated this questionnaire using exploratory factor analysis methods based on data on two studies focused on the effects of inverse kinematics solutions on the SoE. Nevertheless, this questionnaire is still in preliminary phase and will be extended in the future (as there is for instance only a single body ownership question). Another goal of this questionnaire was to be usable as an in-VR questionnaire. Alexandrovsky et al. [Ale+20] have compared in two user studies paper/web questionnaires (outside VR) and those done within VR at the end of an experiment. They observed similar questionnaire results in both cases. While participants reported a lower usability for in-VR questionnaires, the authors also observed higher enjoyment while using these questionnaires as compared to questionnaires outside VR.

Although they are easy to use, questionnaires thus suffer from drawbacks. They are used as a reference but it is hard to use them as a ground truth (see details in Section 1.3.3). This is why other evaluation methods are needed to evaluate the SoE. In the following sections, we present such measures for each component of the SoE. Although we focus on VR, some experiments reviewed here are not made in VR (but could be adapted if necessary) and can be relevant to understand how the SoE is evaluated.

1.3.2 Alternative methods measure the SoE

In addition to questionnaires, other evaluation methods have been introduced to measure the SoE. Nevertheless, we do not know how to directly assess the SoE. Instead, we try to evaluate each component separately, in a way to approximate the SoE, and obtain a surrogate measure. In this way, the evaluation methods are often focused toward a sub-component of the SoE. Remember however that these sub-components are not mutually exclusive and these evaluation methods can have some overlaps, for instance measures evaluating both the SoSL and the SoBO such as the proprioceptive drift (see below).

Evaluation methods focused on the SoA

As mentioned in Section 1.2.1, the SoA is constituted of the feeling of agency (the implicit processes related to the SoA) and the judgement of agency (the explicit processes related to the SoA – those one is aware of). As such, one way to study the SoA (in VR or not) is to focus on the explicit JoA (for instance a participant stating “*I am the one*

who did this”) and carry out an action recognition experiment [Wei+14]. The participant has to judge, according to a video or directly what they see in the VE, if the action they see is theirs or not. They perform a specific hand movement, and the video either shows their hand moving or the hand of an experimenter doing another movement. In VR, the hand movement can directly be manipulated. In a way, participants are asked “*did you do that?*” [Hag17].

However, studies based on the explicit JoA present the cognitive bias of overestimating agency levels or attributing to themselves actions that they have not done [Hag17]. This bias is even stronger when the outcome of the action is positive rather than neutral or negative [Hag17].

In order to avoid these cognitive biases, one can use implicit evaluations such as **intentional binding**, **sensory attenuation** and **biased sensory feedback**. These different types of implicit evaluations are described in the following paragraphs. It should be noted though that these measures have been found to be only weakly correlated to explicit measures [DK14].

Intentional Binding The *intentional binding* effect [HC03] is based on the fact that programming, executing actions and predicting their outcomes influence time perception. In experiments using this effect, participants are asked to report the time (with a small clock in front of them) either of a voluntary action or a resulting sensory event (like a tone) [Hag17]. Voluntary actions are perceived as shifted in time toward their resulting sensory event, and the outcome itself is perceived as shifted backward toward the voluntary action that caused it. Time perception is also affected by attention, drugs intake and visual adaptation [Hag17]. Therefore, shifts in time perception cannot be a diagnostic of the SoA, but the intentional binding effect can be used to evaluate a difference of agency between two conditions.

Sensory Attenuation Sensory attenuation is based on Blakemore’s comparator model of agency [BWF00] described in section 1.2.1. More specifically, it uses the fact that the sensations made by our own actions, which are predictable, are attenuated in comparison to external actions. When one feels agent of their actions, the physiological reaction will be weaker than for actions of other people. This phenomenon has been initially explored in psychophysical experiments studying why some people cannot tickle themselves [WED71; BFW99]. This sensory attenuation effect can be measured by two means.

A first type of measurement is based on a subjective evaluation [WHS11a]. This process can happen in tactile [BFW06; BFW99; TH03], visual [Car+10; GS11] and auditory [Sat08; Mar04] modalities, and the principle is similar for each of them. A protocol that focuses on auditory perception includes two human agents (the participant and an experimenter), and a button in front of each of them. Each button is associated for instance to a tonality with a different frequency. After an acquisition phase (where the participant learns the relation between the actions – button presses – and the sensory consequences – which tonality is played – for their button and the experimenter’s button) the test phase starts with a computer. There are two types of trials: (1) either the participant presses their button and their tonality is played; or (2) the experimenter presses their button and their tonality is played. After a button press, a tone of the same frequency but with a different amplitude (either lower or higher) is played by a computer, and the participant must judge which tonality is the loudest. Regarding visual perception, instead of tonalities, images are shown on a screen. Recent studies however question the effectiveness of sensory attenuation in the visual domain [Sch+18].

A second type of measurement of sensory attenuation uses surface EEG [Küh+11; GS11; Hor15; Wel+17]. The principle is the same as explained previously: either the participant performs a self-action and presses a button producing a tone, or a sound is externally produced by a computer (see Figure 1.6). The ERP² response of sounds produced by our actions is weaker than the ERP responses resulting from external sounds. That is, the N100 component (a negative evoked potential³ elicited 100ms after the stimulus) is smaller in amplitude for actions caused by a participant compared to effects caused by a computer, which thus allows to detect if it is a voluntary action or not.

Biased sensory feedback Other evaluation methods rely on creating an artificial inconsistency between an action predicted outcome and its perceived outcome. For instance, in Jeunet et al.’s experiment in VR [Jeu+18], participants had to perform different hand movements. Users’ real hand were tracked, in such a way that their avatar’s hand moved accordingly. Users’ perceived movement was punctually manipulated in VR by introducing a visually biased feedback such as a temporal delay, two fingers inverted or a finger moving by itself.

By inducing these kind of inconsistencies, studies try to find brain areas related to

2. Event-Related Potentials. This is the measured brain response resulting from a specific sensory, cognitive or motor event[Luc14].

3. Electrical signal produced by the brain in response to an external stimulus.

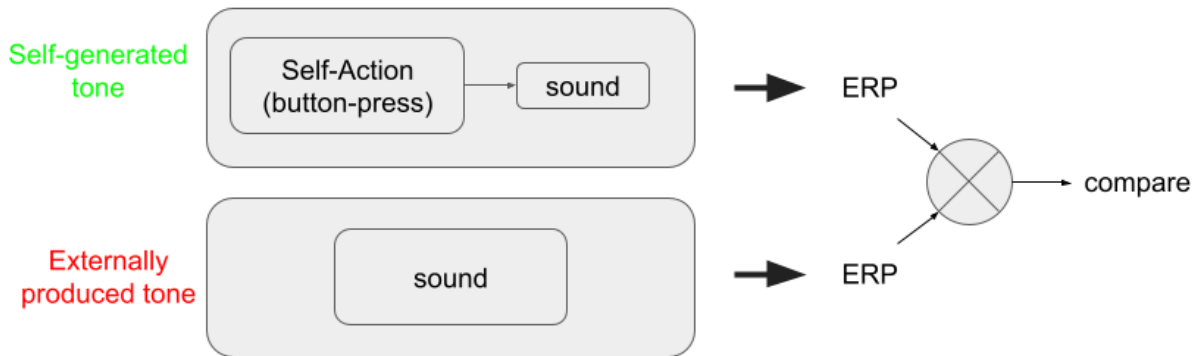


Figure 1.6 – Sensory attenuation evaluation with surface EEG. Either the participant presses a button which plays a tone, or a computer generates a tone without any action from the participant. Comparing the amplitude of the ERP in the two conditions around the N100 component allows to detect if the user was feeling agent or not.

SoA either with fMRI or EEG (see Figure 1.4).

fMRI studies of agency have found that the angular gyrus, in the parietal lobe (see Figure 1.4), is involved in the explicit attribution of the SoA (noticed by brain activation when there is an inconsistency between the expected and perceived outcomes) [FF02; Far+03; Hag17]. A meta-analysis also confirmed that the temporo-parietal junction, including the angular gyrus, is a neural correlate of non-agency [Spe+11]. Some of these studies also associated the dorsomedial prefrontal cortex and the lateral prefrontal cortex with non-agency toward an action. The only area consistently associated with agency is the anterior insula [Hag17] (area found to be engaged in interoceptive awareness of experience [Cri+04]). Finally, as mentioned previously, in their meta analysis, Seghezzi et al. [SGZ19] concluded that SoA specific regions include the left SMA, the left posterior insula, the right postcentral gyrus and the right superior temporal lobe. These studies used a screen and not VR to study the SoA. Nevertheless, they give insights on the neural mechanisms involved in the SoA and which brain regions are expected to be activated in some situations.

Other studies used EEG to find neural correlates. Padrao et al. [Pad+16] noticed that errors due to our actions elicited an N100 in the fronto-central areas while external errors (for instance because of the system) elicited an N400 (negative evoked potential at 400ms after the error is made) in parietal areas. N400s are mainly observed in the case of semantic or conceptual violations [Hag17] (for instance sentences like “*I am going to eat a house*” or observing someone introducing a screwdriver instead of a key into

a keyhole [Pad+16]). In their study, Kang et al. [Kan+15] analysed brain rhythms and suggested that the α band (8-12 Hz) would be the main neural oscillations involved in the SoA. In Alchalabi et al.'s experiment [AFL19], they find an activation in the same frequency band but in different brain regions (in the premotor cortex in the μ band – 8-12 Hz over the sensorimotor cortex). The latter also found, in the case of strong agency, an increase of spectral power in the α band over the fronto-central and central-parietal areas with respect to its average value. In the case of low agency, they observed an increase of spectral power in the α band over fronto-central and left frontal areas. In another study, Jeunet et al. [Jeu+18] observed an increase of spectral power in the θ band (4-8 Hz) over the left fronto-central and parietal areas in high agency conditions, and a decrease of spectral power in the θ band over the right centro-temporal areas.

In VR, apart from questionnaires, the SoA is measured by introducing biased sensory feedbacks [Pad+16; Jeu+18; AFL19], as VR allows to easily perform these manipulations.

Evaluation methods focused on the SoBO

Studies focusing on ownership rely on inducing an illusion of ownership toward a (virtual) body (or a virtual body part) that is not ours. This illusion is induced by either visuo-tactile stimulations (such as in the RHI [BC98]) or visuo-motor synchrony. After the illusion is generated, the SoBO can be measured by different ways.

Visuo-tactile synchrony As explained in the RHI experiment in section 1.2.1, the illusion of ownership is induced by synchronous visuo-tactile stimulations both on participant's real hand and the rubber hand. In their experiment, Moseley et al. observed that the RHI induced a decrease in temperature of the hidden limb, but not for other body-parts [Mos+08]. Likewise, in Kammers' et al. RHI experiment [KRH11], reducing the limb temperature (by using a thermoelectric metal plate connected to a heat pump) strengthened the RHI (and conversely weakened the illusion when warming the real hand).

In their VR experiment, Llobera et al. [LSS13] observed a decrease of the temperature sensitivity (on the palm of the hand) in the synchronous condition, and this sensitivity change correlated with the SoBO (as measured with questionnaires). In this experiment, the asynchronous condition is the condition where the user's avatar is in an inconsistent posture (compared to the participant's posture, for instance having an outstretched arm while the avatar's arm is folded) and the movements of the virtual right arm do not entirely match the real user's movement.

In a non-VR RHI experiment with fMRI, Ehrsson et al. [ESP04] observed a premotor cortex activation when inducing a SoBO illusion, and that this activation is correlated with the strength of the illusion. Moreover, the timing of the illusion is consistent with the one of the activation. In another RHI study, Tsakiris et al. [TLH10] associated the SoBO with the activation of midline cortical structures (composed of the medial prefrontal cortex and the posterior cingulate cortex). The SoBO has also been studied in VR with fMRI. Bach et al. [Bac+12] introduced a VR device suitable for use with fMRI systems to replicate the RHI in VR. It uses a pneumatic device to apply the tactile stimulation on the participant's real hand and a special HMD designed for the use in fMRI environments. In a later experiment, Bekrater-Bodmann et al. [Bek+14] used this device to study the SoBO in VR with fMRI. They found, like Ehrsson et al. works [ESP04] an activation in the bilateral ventral premotor cortex due to visuo-tactile synchrony.

The SoBO has also been studied with surface EEG. Blefari et al. [BCC11] conducted an experiment based on the RHI, with the goal of finding EEG neuromarkers based on Ehrsson et al.'s [ESP04] results. Analyses revealed an increase of the Power Spectral Density in the frontal, parietal and central areas. Note however that it is only an introductory result as they used only $N=5$ participants, 6 trials per participants, 16 EEG channels and a 128 Hz sampling rate. Nevertheless, two years later, Evans and Blanke [EB13] made a similar experiment, this time in VR, with a 64 channel EEG headset. Results show that the SoBO is reflected by a modulation in the θ band (4-8 Hz) in the fronto-parietal cortex, which is consistent with the previous experiment of Blefari et al. [BCC11].

Response to threat (after visuo-tactile stimulation) In some experiments, after the participant has had an illusion of ownership towards a rubber hand or a virtual body, the fake body-part is threatened either actively (someone else approaches with a tool and hits the fake body-part) or passively (by putting threats to avoid in the environment – mainly done in VR setups). This protocol has been introduced by Armel and Ramachandran [AR03] in an experiment similar to the RHI. In the synchronous stimulation condition, the authors noticed a variation of the GSR when the rubber hand was threatened, which was not observed in the asynchronous stimulation condition. It is unknown if participants incorporated external objects (the rubber hand) into their body image or if participants were just subject to demanding effect (that is participants knowing what is the correct answer the experimenters want to obtain, see section 1.4). This is why the authors introduced the GSR as an objective measure of this phenomenon. The

use of threat to test and evaluate the SoBO has then been used in many other experiments and exported to VR [Ehr+07; PE08; Sla+10; YS10; PS13; ZH16]. The response to threat can also be measured by change in body motion [Gon+10; Kil+12; Fri+18] or neuroimagery [Ehr+07; Gon+14]. The same kind of experiment has been made with electrocardiography (ECG). Indeed, the hearth-rate deceleration has been found to correlate with the strength of illusion [Sla+10; PS13]. In their experiment, Ehrsson et al. discovered that threatening a rubber hand that feels “ours” elicits brain activity patterns associated with anxiety, which are the same as when the participant’s real hand is threatened [Ehr+07]. This kind of experiments has been replicated in VR by Gonzalez-Franco et al. where they show a correlation between the motor cortex activation in response to a threat and the SoBO [Gon+14].

In VR, apart from questionnaires, both visuo-tactile synchrony and response to threat are used to measure the SoBO, with the advantage of VR allowing to threaten the virtual body of the user without threatening physically the user’s real body.

Evaluation methods focused on the SoSL

Apart from pathological conditions (e.g. autoscopia – perceiving the surrounding environment from outside the body, from a different perspective), it is complicated to manipulate and study the SoSL without using cameras or VR. Studies focusing on self-location rely on embodying a user in a virtual body, either in 1PP or in 3PP. This illusion is induced by visuo-tactile stimulations (such as in the RHI [BC98]). After the illusion is generated, the SoSL can be measured by different ways.

Visuo-tactile synchrony As mentioned in section 1.2.1, according to Kilteni et al. [KGS12], the SoSL is based on visuospatial perspective, vestibular signals, and tactile stimulations (which are related to personal spaces). For instance, Blanke et al. [BSS15] reviewed neuroscience research of bodily self-consciousness and noticed that the fronto-parietal and temporo-parietal areas are important for the peripersonal space.

Lenggenhager et al. [LHB11] made an experiment in VR with an EEG headset where the point of view is modified. They noticed a modulation in the α band (8-12 Hz) in the sensorimotor cortex bilaterally. Moreover the α band power in the median prefrontal cortex (mPFC) is correlated with the degree of experimental manipulation of the self-location.

Proprioceptive drift This method uses the proprioception (the feeling of body position and movement [TA18]). In the RHI [BC98], participants were also asked to blindly point where they felt their real hand was located, before and after the stimulation. In the synchronous stroking condition, participants tended to point toward the rubber hand. Proprioceptive drift is the difference between the position before and after the stimulation. This value has been found to be correlated with the SoBO toward the rubber hand [BC98; TH05; Ehr05]. The fact that participants point toward the fake hand after the stimulation indicates that their peripersonal space (and thus their SoSL) has been modified. Note that correlations have been found with the SoBO although we evaluate where the body is (and thus the SoSL) : that is because the SoBO and SoSL are tightly coupled, in the way that in both SoBO and SoSL manipulations, the whole body-scheme is updated. Still, because this measure asks the participant to indicate where the hand/body is located, we wanted to include it in the SoSL measurement category.

This method has then been generalised to virtual arm [Sla08] or full-body in VR [Len+07]. In their study, Normand et al. [Nor+11] used another kind of proprioceptive drift in an RHI-like experiment: they embodied participants in avatars with an inflated belly and they had to estimate the size of the belly before and after the stimulations. They found that the estimation of the belly size of the avatar correlates positively with the SoE as measured using their questionnaire (a mix of questions based on Botvinick and Cohen RHI [BC98], new and exploratory questions).

Response to threat It is also possible to measure the SoSL by threatening the avatar to the perceived self-location. Indeed, Ehrsson et al. [Ehr07] measured the GSR to evaluate the SoSL in the situation of a threat. They noticed a variation of the GSR after a threat toward the perceived self-location. This gives insight of the strength of the illusion. The difference with the SoBO is in the protocol, in which participants see themselves in 3PP, but in both cases the SoBO and the SoSL evaluated via response to threat reflects the experienced fear and anxiety due to the illusion.

Locomotion Task A locomotion task is an action-based judgement, where participants must move to their perceived location. Generally in locomotion tasks, after the synchronous visuo-tactile stimulation, participants are blindfolded (or the HMD is blacked out) and displaced. They are then asked to get back to their previous position [Len+07]. In most studies with a 3PP using this evaluation method, participants tend to relocate them-

selves 10 to 30 cm toward their perceived self-location from their initial position, so this method evaluates a compromise between participants' real position (their physical body) and their perceived self-location [Lop+15; Nak+20]. The locomotion task suffers from the limitation that the participant has to move which updates somatosensory, vestibular and interoceptive signals [Nak+20].

Mental Imagery Task To counteract the limitation of the locomotion task, mental imagery tasks have been introduced, so that the participant could remain motionless. One of them is the “*mental ball dropping*” task: participants are asked to imagine themselves drop a ball they would hold in their hand. By means of two button presses, they first indicate when they drop the ball, and press another time to indicate when the ball is supposed to touch the floor [LMB09; Ion+11; Bou+17]. Researchers observed that, after synchronous visuo-tactile stimulation, participants' estimates of the time required for the ball to reach the ground increased or reduced depending on whether they felt located above or below their body [Bou+17]. In their experiment, Nakul et al. [Nak+20] used a rolling ball: a red ball appears in front of the participant, and rolls at a constant speed toward “them”. After a certain delay, the vision in the HMD is blacked out and the participant must indicate with a button-press when they think the ball hit them (see Figure 1.7). This measure revealed higher self-location toward the avatar and higher reports of presence compared to the locomotion task [Nak+20], as participants could remain motionless. The reason could be that mental imagery tasks allow the user to detach from sensory information from the real environment whereas locomotion tasks force the user to walk in the real environment and thus shift attention to their bodily signals.

Tasks under a 3PP Other experiments can require participants to perform different tasks in 1PP and in 3PP. For instance, in an fMRI study, Vogeley et al. [Vog+04] asked participants to count red balls from multiple viewpoints (not in VR but using a screen) in 1PP and in 3PP while measuring participants' brain activity with fMRI. Analyses revealed in both cases an activation of occipital, parietal and pre-frontal areas, and a deactivation in mesial cortical and lateral superior temporal areas bilaterally. They also observed an increase of activity in the 1PP condition relative to the 3PP condition in the posterior cingulate cortex and superior temporal cortex. These kind of experiments are a way to evaluate and manipulate the SoSL.

In VR, apart from questionnaires, the SoSL is mainly measured by introducing a threat

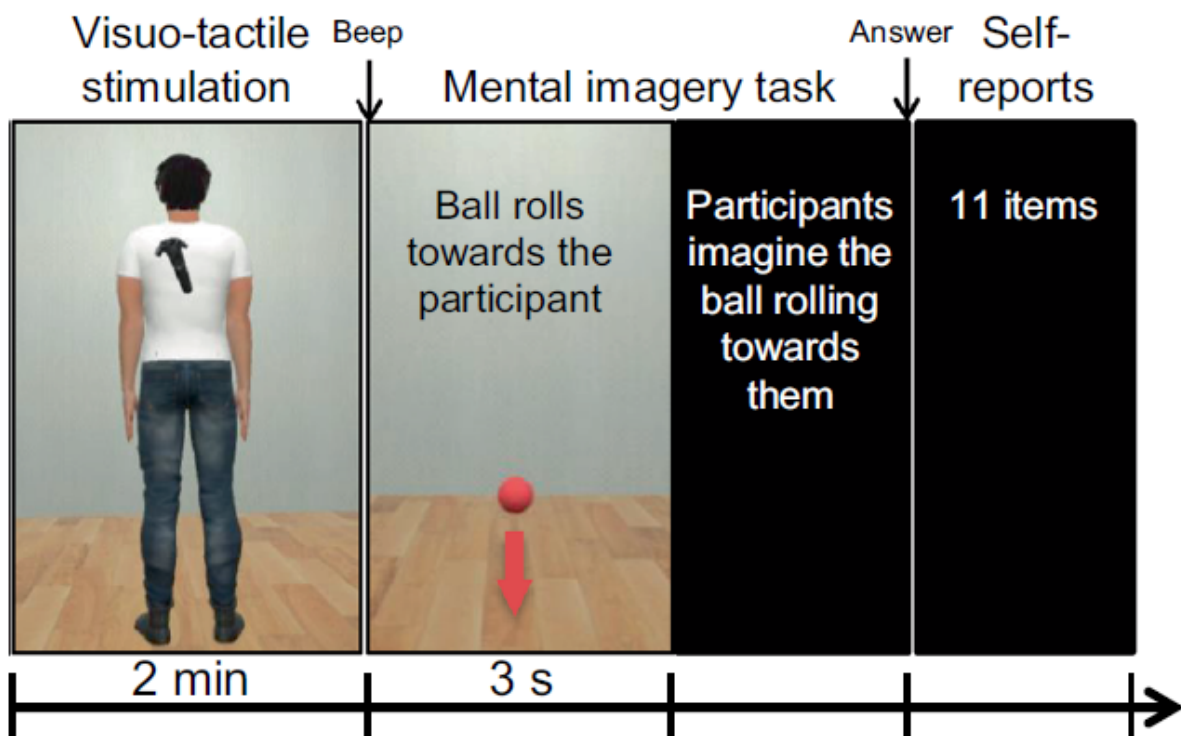


Figure 1.7 – Mental imagery task as described in [Nak+20]. A red ball appears in front of the participant, and rolls at a constant speed toward “them”. After a certain delay, the vision in the HMD is blacked out and the participant must indicate with a button-press when they think the ball hit them. Figure from [Nak+20].

or using locomotion/mental imagery tasks. One or the other can be more appropriated depending on the experiment (see Section 1.3.3).

1.3.3 How to chose a way of evaluating Virtual Embodiment?

Facing all these evaluation methods, one can wonder how to chose a way of evaluating VEmb? First, we define different criteria that are important to consider in VR, then we discuss the advantages and drawbacks of the previously mentioned evaluation methods.

Criteria for evaluation methods

In order to compare the different evaluation methods of VEmb, we propose different criteria we believe are important for a VR use case. We have identified 3 types of evaluation criteria that relate to **ecological situation**, **subjectivity of the measurement** and the **processing of the data**.

The criteria are separated into two categories, depending on whether they relate to the measures or the protocol. Indeed, some measurement tools impose constraints to the user, and some experimental protocol can be used with different measurement tools.

Measures-related criteria:

- **Protocol dependent**: The measure requires the use of a particular experimental protocol.
- **Ecological**: The measure forces, restricts or prohibits the user to do some actions.
- **Self-reported**: The measure is a subjective evaluation from the user (given orally or written).
- **Second task**: The measure is a task in itself (accessing the measure requires a particular task from the participant).
- **Real-time measurement**: Data acquisition is in real-time (in the order of milliseconds).
- **Real-time processing**: Data processing (and interpretation) is in real-time.
- **Cognitive demand**: The measure uses cognitive functions of the user (attention, memory, inhibition).
- **Need reference value (e.g. rest)**: The measure has inter-personal variations and needs a reference value to be interpreted.
- **Sensitive to artefacts**: Measure acquisition contains artefacts.

Protocol-related criteria:

- **Ecological:** The measure forces or prohibits the user to do some actions.
- **Second task:** An additional task from the participant is necessary to access the measured process.
- **Cognitive demand:** The protocol uses cognitive functions of the user (attention, memory, inhibition).
- **Emotionally unpleasant:** The protocol provokes unpleasant emotions to the user (boredom, fear, anger, unease, discomfort, etc.).
- **Need other people:** The protocol requires other people (interviewer, observer, etc.).

Advantages and inconvenients of current evaluation methods of Virtual Embodiment

Although they are easy to use, questionnaires suffer from drawbacks. Indeed, as they are self-reported, the answers are subject to the interpretation of questions and cognitive biases [JM14; Hag17]. Furthermore, questionnaires require to perform a double task (the first task being the experimental protocol and the second task being answering the questionnaire) and the evaluation by itself cannot be in real-time: it is only at the end of the task, requiring participants to “remember” how they felt during the experiment. Moreover, it is possible to create a questionnaire about a totally new feeling and still get relevant questionnaire responses. Slater [Sla04] created a fake attribute being the “*colourfulness of the experience*” and created an associated set of questions. The analysis revealed significant differences between two days, one being “*more colourful than the other*”. This however has no meaning, insisting on the importance of carefully designing VEmb validated and standardised questionnaires. Questionnaires are used as a reference, but it is hard to use them as a ground truth. In this way, it may be worth to couple questionnaires with at least one other of the methods reviewed. We represent and compare all of them in tables (see Table 1.3 and Table 1.4).

Abdulkarim et al. [AE16] moved participants’ hand without them noticing, in a RHI setup. They observed that the strength of the illusion is not linked to changes in hand proprioception (as measured via proprioceptive drift), questioning the pertinence of proprioceptive drift for evaluating the SoBO. Correlations have been found between the proprioceptive drift and the SoBO. Nevertheless, some studies found that a change of proprioception can occur with no impact on the hand SoBO, that may be integrating the rubber hand in one’s body surrounding while not integrating it as one’s hand [HCS04;

HSS06; MHE08].

Some experiments are bound to particular protocols. For instance, the response-to-threat evaluation method forces experimenters to introduce a threat. But has a threat positive or negative impacts on VR experiments? This is the question explored by Fribourg et al. [Fri+21] by introducing a threat and verify if it would impact the participants' behaviour after the threat and measures of the SoE. Their results suggest that a threat has an impact on the participants' behaviour (after the threat) but no impact on subjective and objective measurements of the SoE, so, depending on the scenario, this evaluation can be used (although a repetitive threat could impact participants well-being). Physiological measures also have been used in combination with response to threat. While they could be used for real-time evaluation of VEmb, they also have drawbacks: they are subject to noise sensitivity and often need a reference value. The main drawback of physiological measures is their lack of specificity. Indeed, modulations of heart rate or GSR can be due to alterations of the SoE, but also to other internal or external factors such as the circadian rhythm or modulations of room temperature, respectively.

Neuroimagery instruments are also promising measures. fMRI offers a good spatial resolution (in the order of millimetres) which enables the identification of brain structures related to VEmb. However, it suffers from poor temporal resolution (around 3-6s) and portability, which complicates real time evaluation and the use in any real scenario [Wei+04]. Moreover, fMRI are expensive, and combining fMRI with a VR headset is complicated, although some devices exist [Bac+12]. On the contrary, EEG has a rather poor spatial resolution (in the order of centimetres) but offers a high temporal resolution (around milliseconds) and high portability, which makes it a better candidate for real time evaluation and the use in VR [Sau+09; Geo+12; Mul+06]. EEG headsets are sensitive to electromagnetic noise and combining them with VR headsets brings challenges. However, multiple studies showed that it is feasible. Tauscher et al. [Tau+19] found that the EEG signal quality can be improved by reducing physical strain on the EEG headset. Si-Mohammed et al. showed that using an EEG headset combined with an Hololens is possible and even that small head movements can be allowed when using the EEG headset.

Component	Evaluation method	References
SoE	Questionnaires	[BC98; RL20; PG21; Eub+21](non exhaustive)
SoA	Intentional Binding	[HC03; Hag17]
	Sensory Attenuation	[WHS11a; BFW06; BFW99; TH03; Car+10; GS11; Sat08; Mar04; Hor15; Wel+17]
	Biased sensory feedback	[FF02; Far+03; Hag17; Spe+11; Pad+16; Kan+15; AFL19; Jeu+18]
SoBO	Visuo-tactile synchrony	[Mos+08; KRH11; ESP04; TLH10; BCC11; EB13]
	Response to Threat	[AR03; Ehr+07; PE08; Sla+10; YS10; PS13; ZH16; Fri+18; Gon+14]
SoSL	Visuo-tactile synchrony	[LHB11; BSS15]
	Proprioceptive Drift	[BC98; TH05; Ehr05; Sla08; Len+07; Nor+11]
	Locomotion Task	[Len+07; Lop+15; Nak+20]
	Mental Imagery Task	[LMB09; Ion+11; Bou+17; Nak+20]
	Tasks under a 3PP	[Vog+04]
	Response to Threat	[Ehr07]

Table 1.2 – Summary of the different evaluation methods used in the literature to measure the SoE in VR.

Measure	Protocol dependent	Ecological	Self-reported	Second task	Real-time measurement	Real-time processing	Cognitive demand	Need reference value	Sensitive to artifacts
Time perception (subjective)	intentional binding	obligation	yes	yes	no	no	attention	yes	no
Interview/sound perception	sensory attenuation	obligation	yes	yes	no	no	attention	yes	no
EEG	no	restrict	no	no	yes	possible	focus	yes	yes
fMRI	no	restrict	no	no	no	possible	focus	yes	yes
Temperature decrease	no	free	no	no	?	?	?	yes	?
Temperature sensitivity	no	free	no	no	?	?	?	yes	?
GSR	no	free	no	no	no (seconds)	no	?	yes	yes
Heart-Rate deceleration	no	free	no	no	yes	yes	?	yes	yes
Behavioural response to threat	response to threat	obligation	no	no	yes	yes	?	no	no
Interview/dis-tance perception	proprioceptive drift and locomotion task	obligation	yes	yes	no	no	attention, memory	yes	no

Table 1.3 – Comparison of all reviewed measurement methods of VEmb according to our defined criteria. Cells with a “?” are missing information.

Component	Protocol	Ecological	Second task	Cognitive demand	Emotionally unpleasant	Necessity of other people
SoA	Intentional Binding	obligation	yes	attention	-	no
	Sensory Attenuation	obligation	yes	attention	-	not necessarily
	Biased Sensory Feedback	free	no	-	-	no
SoBO or SoSL	Visuo-tactile synchrony	restrict	no	-	-	yes
	Response to threat	free	no	-	fear	not necessarily
SoSL	Proprioceptive drift	obligation	yes	attention	-	no
	Locomotion task	obligation	yes	memory	-	no
	Mental Imagery task	obligation	yes	attention	-	no
	Tasks in 3PP	obligation	yes	attention	-	no

Table 1.4 – Comparison of all reviewed protocols linked to VEmb according to our defined criteria.

1.4 Discussion

The goal of this chapter was to review the current knowledge of the SoE in VR and its different evaluation methods. We detailed in section 1.2 the current separation of the SoE in VR in 3 sub-components (the SoA, the SoBO and the SoSL) and their possible origins. Their inter-relation was also discussed as well as the perceptual and behavioural impacts of the SoE on users. Then, in section 1.3, we reviewed the different evaluations methods of the SoE in VR. We first observed the emergence of new standardised questionnaires. Their usage would improve experiment comparability and help SoE research. Then, additional evaluation methods were discussed, based on what was the target to measure: does the user feel agent; does the user feel ownership over a body or a body-part; and where the user feels their body/body-part to be located, echoing the three sub-components of the SoE. Finally, we suggest criteria to compare the different evaluation methods of VEmb and some benefits and drawbacks of some measurement methods.

What measure to chose depends on the use case and we hope the criteria we propose can help the reader to select one. These are a first suggestion and this list might be refined in the future, with the consideration of real usage case (more details in chapter 4). In VR, having an evaluation method that is real-time (in the order of milliseconds) and objective (i.e. independent from the user's emotional/cognitive/motivational state), while being ecologically valid and reliable, would greatly help embodiment research. Unfortunately, this is not an easy task. First, not all measures presented here have real-time measurement. The remaining measures are ECG, behavioural response to threat and EEG. As explained in subsection 1.3.3, ECG is not necessarily specific as it can be impacted for instance by the temperature of the room. Behavioural response to threat, while real-time in the sense of "when the user is threatened, it is possible to measure their reaction", is not ecological since it is not realistic to threaten constantly the user. EEG allows real-time measurement suitable for VR scenarios. However, EEG signal-to-noise ratio is still poor, it is greatly impacted by (mainly head) movements making the measure less accurate. It also forces the user to wear another headset, which can be cumbersome. While some studies have found neural correlates for the SoA and the SoBO using EEG, it is not yet the case for the SoSL. Moreover, detecting these correlates with EEG is a first step but it does not necessarily mean that it is yet possible to process in real-time the EEG signals to measure the SoA or the SoBO. Improvement in EEG processing, with better knowledge of the SoE will help to this objective.

As Kilteni et al. state [KGS12], it is yet unknown if the SoE is time-varying, and if so, how it evolves during an experiment. Moreover, we also reviewed in subsection 1.2.3 that the SoE has impacts on users. It is therefore important to have a real-time and reliable measure, without a second task, that can be used as a ground truth in order to correctly study the impacts and effects of embodiment on users, especially when VR is becoming more and more accessible for the general public. As of today, the main evaluation method remains questionnaires and subjective reports. The other presented evaluation methods were found to be correlated with some questionnaires. However, it is unclear whether questionnaires and other measures evaluate exactly the same phenomena. For instance, only a weak correlation between explicit judgement of agency and explicit measures has been found [DK14]. This should be explored in future experiments, with the increasing knowledge of the cognitive processes related to VEmb. Finally, these correlations should be confirmed with the usage of the standardised questionnaires mentioned [RL20; PG21].

Questionnaires and virtual embodiment research are based on the RHI [BC98] and on full-body illusions [Ehr07; Len+07]. But can all these works based on the RHI be considered as correct? Indeed, several recent studies of Lush et al. [Lus20; Set+21] addressed the issues of demand characteristics and imaginative suggestibility of the RHI. Demand characteristics are the impact of participants knowing what is the correct answer the experimenters want to obtain. For instance in the RHI, experimenters expect participants to feel ownership toward the rubber hand in the synchronous condition but not in the asynchronous condition. Participants do not necessarily know this, but they can guess the expected result. As reported in Seth et al. [Set+21], the participants not only will tend to respond to expected answers and behaviour, but demand characteristics also change the subjective experience of the experiment [KC89; Ols+20]. Moreover, in another experiment, Lush et al. [Lus20] described precisely the RHI to participants, and asked them what their expectations were, without actually doing the RHI experiment. They found that, across synchronous and asynchronous conditions, participants expected the same pattern of replies (whether considering subjective questionnaires or proprioceptive drift). It is therefore important to control demand characteristics in experiments. Nevertheless, Reader [Rea21] replicated Lush et al. [Lus20] experiment: participants were presented the RHI with a video and were asked what they expected in synchronous and asynchronous conditions. They answered with rating questionnaires but also free responses. Participants expected greater illusion in the synchronous condition compared to the asynchronous condition. Interestingly, these expectations may be driven (at least partially) by exposure to

the questionnaire items, as suggested by the free responses [Rea21].

Imaginative suggestions are “requests to experience an imaginary state of affairs as if it were real” [KB01]. Suggestibility, also called trait phenomenological control (PC), is measured by means of hypnotisability scales, which evaluate “individual differences in the ability to generate experience in response to imaginative suggestion” [Lus+20]. Still in Lush et al.’s experiment [Lus+20], they found that trait PC (i.e. suggestibility) correlated with experienced ownership as measured by questionnaires or proprioceptive drift. That is, participants who have a higher trait PC experience a stronger illusion. Furthermore, they analysed in another study how the trait PC variability over participants and their proportion might affect results of RHI studies with a relatively small sample size. In other words, what is the impact of having a majority of high PC participants (or respectively a majority of low PC participants). They observed that when there is a majority of high PC participants, finding RHI evidence is almost guaranteed, while when having only low PC participants, the RHI appeared only half of the time (they state that it even drops down to only 4% when considering only questions and ratings about ownership). Finally, Lush et al. insist on the importance of controlling the demand characteristics of the RHI (and more generally in any experiment), especially in regards to the effect of imaginative suggestibility. While this has only been tested, as of now, for RHI studies, it is more than likely to be an issue for similar embodiment illusions like full-body illusions. In this way, it is important to understand (but still unknown) if the imaginative suggestion effect explains all the effect observed in the RHI or what effects are effectively occurring. As explained before, not only this has an impact on the experienced illusion and thus the subjective reports, but also on proprioceptive drift. Moreover, imaginative suggestion has also been found to impact skin conductance response (for instance with changes in facial expression [LEF90]) and fMRI measures and histamine reactivity [Lus+19]. The authors however do not mention the other measures like response to threat and this should be investigated. Therefore, implicit measures of embodiment must also be interpreted with care, as, without valid subjective reports of embodiment, they may be just proxy measures of something else (for instance proprioceptive drift may just be a measure of confusion about the location of the hand) [Lus20].

Despite all of this, Ehrsson et al. [Ehr+22] reanalysed Lush et al.’s [Lus+20] data and found no specific relationship between hypnotic suggestibility and the rubber hand illusion. In another article, Slater and Ehrsson [SE22] also made new analyses of Lush et al.’s data. They found that while hypnotic suggestibility “modestly influences” the

subjective reports, the major difference between synchronous and asynchronous conditions remains explained by the multisensory integration from the RHI. Moreover, they observed that the participants' expectation toward the RHI was negligible to explain the effect. Trait suggestibility may modulate the illusion as an inter-subject factor, but the RHI remains a multisensory bodily illusion [SE22]. Finally, they observed the same results with proprioceptive drift. Further studies should be made in order to investigate if hypnotic suggestibility impact other SoE measures or if it is negligible. Most studies presented in this chapter are based on Botvinick and Cohen's RHI [BC98], especially experiments trying to explain cognitive processes that might be involved in the sense of ownership. Nevertheless, we should keep in mind the final and concrete use case of VR, and studies should also focus on the SoE in VR in real scenarios. This point will be discussed in detail in **chapter 4**.

Finally, as presented in section 1.2, the definition of the SoE is evolving, with the attempts to create new standardised validated questionnaires [PG21; RL20], and deviating from the 3 sub-components of the SoE defined by Kilteni et al. [KGS12]. Peck and Gonzalez-Franco [PG21] suggested motor control, tactile sensations, external appearance and response to an external stimuli, echoing De Vignemont's categories of measures of embodiment being spatial measures ("is the space surrounding the embodied object processed as peripersonal space"), motor measures (does one feels that the embodied object "directly obeys one's will" – similar to the SoA) and affective measures (is the embodied object "protected from hazardous situations" – already evaluated with galvanic skin response but not with questionnaires) [Vig11]. Likewise, Roth and Latoschik [RL20] suggested a new dimension of embodiment consisting in change in the perceived body schema. The proprioceptive drift measure ("pointing where my hand or body is") was categorised in the SoSL category, although correlations were found with the SoBO [BC98]. We categorised like this because it was referring to "where the body is", although in the RHI experiment, the whole body scheme is updated, explaining this overlap of the SoBO and SoSL components. In other words, the SoBO and the SoSL could be both part of a broader "change in perceived body schema" [RL20].

1.5 Conclusion

This chapter reviewed the current state of the knowledge about virtual embodiment, its impacts on users and the existing evaluation methods. Questionnaires, the current

reference measures, are constantly evolving, with the rise of new competing standardised questionnaires [RL20; PG21]. The definition and boundaries of embodiment themselves are redefined, emphasising the need to have better measurement methods to better understand this phenomenon.

STUDY OF THE RELATIONSHIP BETWEEN THE SUB-COMPONENTS OF THE SENSE OF EMBODIMENT

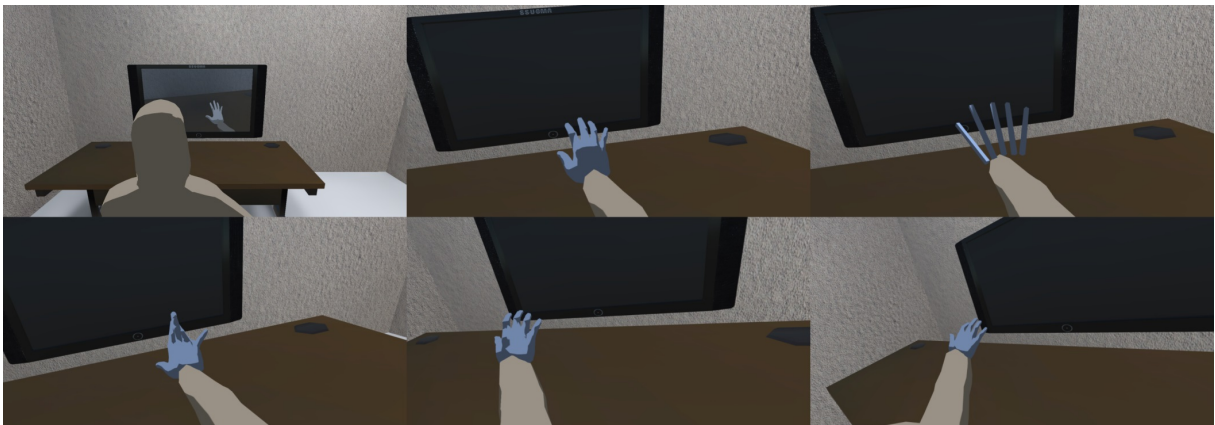


Figure 2.1 – This experiment assessed the sense of embodiment during right-hand movements with different levels of agency, different levels of virtual hand realism, and different levels of self-location. (Top-left) Overview of the Virtual Environment used in the experiment. The participant’s avatar is seated on a chair, in front of a table where a screen displaying videos and signals is positioned. (Middle-top and top-right) First-person perspective (1PP) of the anthropomorphic cartoon hand (*Anthropomorphic-hand*) and stick-fingers hand (*Stick-fingers*). Bottom (from left to right): inverted 2nd and 4th fingers (*Manipulated*) in 1PP, third-person perspective in peripersonal space (3PP – PP), third-person perspective in extra-personal space (3PP – EP).

Abstract: This chapter explores the relationship between the sub-components of the sense of embodiment (SoE). We wish to extend the understanding of the SoE and the interactions between its sub-components. Our research question is “Can each sub-component of the SoE be independently manipulated?”. To address this question, we designed a within-subject experiment where 47 right-handed participants had to perform movements of their

right-hand under different experimental conditions impacting the sub-components of embodiment: the SoA was modified by impacting the control of the avatar with visual biased feedback, the SoBO was altered by modifying the realism of the virtual right hand (anthropomorphic cartoon hand or non-anthropomorphic stick “fingers”) and the SoSL was controlled via the user’s point of view (first or third person). After each trial, participants rated their level of agency, ownership and self-location on a 7-item Likert scale. Results’ analysis revealed that the three components could not be selectively altered in this experiment. Nevertheless, these preliminary results pave the way to further studies.

2.1 Introduction

Many studies presented in chapter 1 showed that the three components of the SoE are closely related between each other (see Figure 1.5 on page 29). However, the relationships and interactions between these three components still remain unclear, especially in a VR context, as many of the existing studies mainly focused on 1 or 2 components at the same time. In this chapter, our aim is to deepen the understanding of the sense of embodiment (SoE) and the interactions between its components by 1) experimentally manipulating independently the sense of agency (SoA), sense of self-location (SoSL) and sense of body ownership (SoBO) in VR, and 2) understanding to what extent each component can be selectively altered. To do so, we designed a within-subject experiment where 47 right-handed participants had to perform movements of their right-hand under different experimental conditions impacting the components of the SoE (see Figure 2.1): the SoA was modified by impacting the control of the avatar with a biased visual feedback, the SoSL was controlled via the user’s point of view (first-person, third-person in peripersonal space or third-person in extra-personal space) and the SoBO was altered by modifying the realism of the virtual right hand (anthropomorphic cartoon hand or non-anthropomorphic “stick fingers”). After each trial, participants rated their levels of agency, ownership and self-location on a 7-item Likert scale. To the best of our knowledge, this is the first time that the SoA, SoSL and SoBO are manipulated in a same VR experiment to study their interactions.

This chapter is structured as follows. Section 2.2 presents the experimental protocol and design as well as our research hypotheses. Our results are analysed in Section 2.3 and discussed in Section 2.4. Finally, Section 2.5 concludes this work and presents some future works.

2.2 Material and Methods

In this section we present the participants, experimental protocol and measures used in our study and detail our research hypotheses.

2.2.1 Participants

Fifty (50) participants were originally recruited in the experiment. Three participants were removed due to issues during the recording of their data. So, a total of 47 participants (27 men, 20 women, 28.43 ± 11.05 year-old (mean \pm SD)) took part in the experiment. All participants had normal or corrected-to-normal vision. As the questionnaire was only in French, the population was restricted to French speaking people. Because we asked participants to perform right-hand movements, we also recruited only right-handed persons. Indeed, it is unknown, to the best of our knowledge, if our dependent variables in this study are impacted by being right- or left-handed. The experimental protocol has been approved by the internal review board of Université de Nantes (reference number 15122021).

2.2.2 Experimental manipulation of the components of the SoE

Since there are multiple ways to study each component of the SoE (i.e SoA, SoSL and SoBO) as well as to study the impact of each manipulation to these components, we wanted to know to what extent each component could be selectively altered, based on the existing literature. In this section, we define and detail the manipulations implemented in the experiment.

Agency Manipulation

The SoA is manipulated by means of biased visual feedback (the outcome of an action does not match the intended action) [Kan+15; Pad+16; Jeu+18]. In this experiment, there are two agency conditions:

- *Synchronous* condition, where there is no manipulation on participant’s hand tracking. There is a direct mapping from user’s real hand movement to the avatar’s hand;
- *Manipulated* condition, where the visual feedback of the participant’s hand movement is biased by one of three manipulations (see below).

The SoA is manipulated following Jeunet’s et al. experiment [Jeu+18] in three different ways: (i) adding 1s of temporal lag in the user’s movement; (ii) having the thumb moving by itself; or (iii) inverting the 2nd and 4th fingers (see Figure 2.1). These three manipulations were kept in order to add variety to the experiment and be more representative of tracking issues that could alter the SoA. These manipulations of the SoA are nonetheless not distinguished in the experimental protocol nor in the analysis (as they were found to all have an effect in [Jeu+18]).

Self-Location Manipulation

The SoSL is manipulated by changing the visuospatial perspective of the user (either 1PP or 3PP) [Len+07; Sla+10; Bou+17; Ehr07]. In this experiment, there are three self-location conditions (see Figure 2.1):

- 1PP condition, where the user’s visuospatial perspective matches the avatar’s position;
- 3PP-PP condition, where the visuospatial perspective is shifted 20cm to the right of the user¹, remaining in the peripersonal space – everything at grasping range.
- 3PP-EP condition, where the visuospatial perspective is shifted 50cm to the right of the user, being in the extrapersonal space – anything being out of reach.

Indeed it was shown that the visuospatial perspective has an impact on the SoBo but only in certain conditions [MS14]. In their experiment, Maselli and Slater [MS14] changed the visual perspective of participants in a VR experiment: either (i) in 1PP with a total overlap of the participant’s real body and the virtual body; (ii) in a 3PP shifted around 25cm to the right with the left leg of the participant being near the right leg of the avatar; or (iii) in a 3PP shifted 80cm to the right of the virtual body, so that there is no overlap at all between the participant’s real body and the virtual body. The authors observed that the SoSL was altered in both 3PP conditions, but the SoBo was preserved in the 3PP at 25cm compared to the 3PP at 80cm. This is what we wanted to replicate in this experiment, in order to selectively alter each component. However, due to technological constraints, the virtual body could not be 80cm away from the participant since, at that distance, the hand tracking was lost when not looking at the hand. Indeed, when the visuospatial perspective is shifted laterally to the right, the users turn their head to the left to see the virtual body (see Figure 2.1) while their real hand stays in front of them. In that configuration, the VR headset was unable to perform stable hand-tracking,

1. In the virtual space, 1 unit of distance consists of 1 meter, as defined in Unity.

the real hand of the participant being outside of the range of the HMD’s sensors. We experimentally found out that the avatar could be located at a maximum of ~ 50 cm away from the participant for hand-tracking to work for an average participant. Fortunately, 50cm is at the border of peripersonal space (reported at 45 ± 7 cm in [Rab+20]).

Body-Ownership Manipulation

In VR, the SoBO can be manipulated with visuo-tactile asynchronous stimulations [BC98] or changing the appearance of the avatar’s hand [Arg+16; LJ16; Che+18]. In this experiment, there are two body-ownership conditions:

- *Anthropomorphic-hand* condition, where the avatar has an anthropomorphic cartoon hand (see Figure 2.1);
- *Stick-fingers* condition, where the avatar has a non-anthropomorphic hand with sticks as fingers (see Figure 2.1).

Because we are forced to have movements due to the study of the SoA, we could not use visuo-tactile asynchrony. In this way, we decided to change the appearance of the avatar’s hand to alter the SoBO like previous studies [Arg+16; LJ16; Che+18]. In their experiment, Lin and Jörg showed that a SoBO can be created with different realistic representation of a hand, being a realistic hand, a toony or very toony hand, a zombie or robotic hand or even a wooden block [LJ16]. Nevertheless, the effect is the weakest for the non-anthropomorphic block model. Moreover, it has been shown that in order to induce ownership toward an external object, a basic morphological similarity with the real body part (or whole body) is needed [AR03; Tsa+10; TH05].

We expect the SoBO to be lower with a non-anthropomorphic hand, similar to the wooden block in Lin’s and Jörg’s [LJ16] experiment. Since we wanted participants to perform hand movements and more specifically fingers movements, this non-anthropomorphic hand needed to have “fingers” for the user to be able to reflect upon their movements. We thus decided to have 5 “sticks” as fingers, aligned (i.e., there was no “thumb-like” position for any of the sticks) and floating in front of the avatar’s wrist (see Figure 2.1). Moreover, the sticks are not attached to the wrist to make it less anthropomorphic (as a SoBO was possible with a robotic hand in [LJ16]).

On the contrary, in the condition where a high ownership illusion was expected we choose to use an anthropomorphic cartoon hand (see Figure 2.1). This was preferred over a realistic hand for two reasons. The first one being that an uncanny valley effect can exist to a certain extent, and the second being that otherwise, the virtual hand would

have to match the shape of the hand and skin colour of each participant to not be a potential impacting factor [Mor12; LLL15b]. It has also been found that a SoA is still possible for less realistic hands [Arg+16]. In *3PP-PP* and *3PP-EP* conditions, the user could in addition see the avatar’s head (only if they turned their head, which they were instructed not to do). Still, as a safety measure, the avatar had a hood covering all his head, such that the avatar’s face could never be seen from a 3PP (see Figure 2.1).

With two conditions for the SoBO and SoA, and three for the SoSL, there is a total of $2 \times 2 \times 3 = 12$ distinct conditions explored in this experiment.

2.2.3 Design and Hypotheses

The experiment followed a full factorial $2 \times 2 \times 3$ design: *SoA-manipulation* (*Synchronous* vs *Manipulated*), *SoSL-manipulation* (*1PP* vs *3PP-PP* vs *3PP-EP*) and *SoBO-manipulation* (*Anthropomorphic-hand* vs *Stick-fingers*). All variables were within-subjects. The goal was to study the interaction between the SoA, the SoSL and the SoBO manipulations on the SoA (resp. SoSL and SoBO) as evaluated by our custom questionnaire (1 question on a 7-item Likert scale for each component). The resulting SoA (resp. SoSL and SoBO) score is computed by averaging over repetitions. Our hypotheses regarding the SoA score were:

H1 Higher score in *Synchronous* over *Manipulated* [Jeu+18].

H2 No difference between *Anthropomorphic-hand* and *Stick-fingers* [Arg+16; LJ16; Che+18].

H3 No difference between *1PP*, *3PP-PP* or *3PP-EP* [Dav+06].

Our hypotheses regarding the SoSL score were:

H4 No difference between *Synchronous* and *Manipulated* [Dav+06].

H5 No difference between *Anthropomorphic-hand* and *Stick-fingers*.

H6 Higher score in *1PP* compared to the two 3PP conditions [MS14].

Finally, our hypotheses regarding the SoBO score were:

H7 Higher score in *Synchronous* over *Manipulated* [KE12].

H8 Higher score in *Anthropomorphic-hand* over *Stick-fingers* [LJ16; Arg+16; PE08].

H9 No difference between *1PP* and *3PP-PP* and a higher score in *1PP* over *3PP-EP* [MS14].

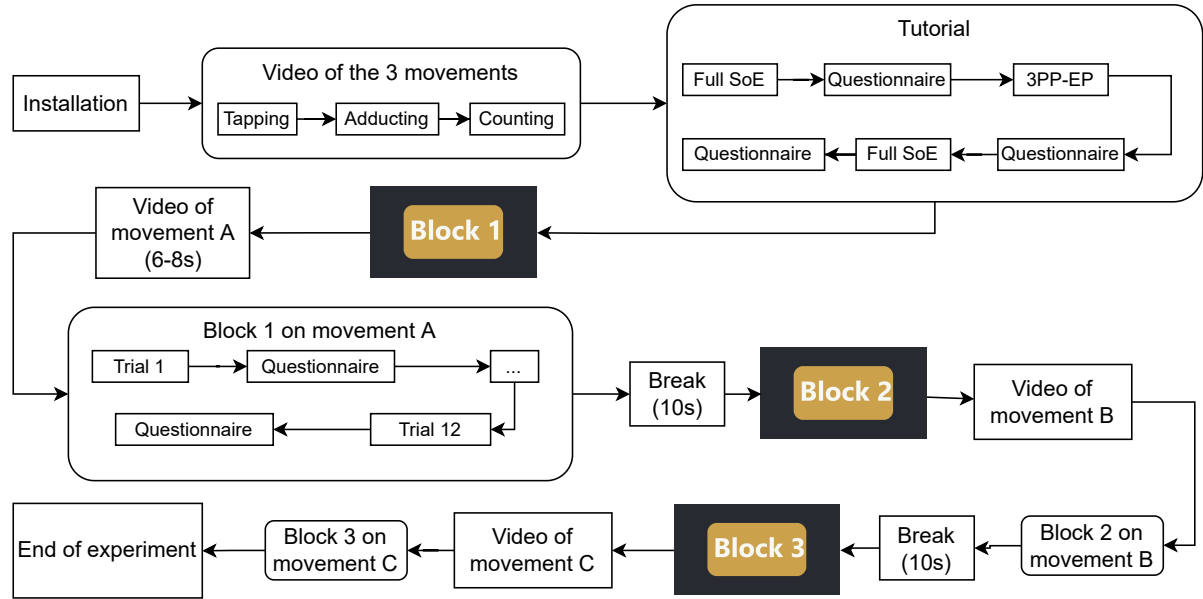


Figure 2.2 – Experimental protocol. The "Full SoE" condition in the tutorial represents the *Synchronous* and *Anthropomorphic-hand* and *1PP* condition together. Movement A, B and C are the three movements (tapping, adducting and counting) counter-balanced between the participants in order to avoid any order effect.

2.2.4 Apparatus

In this study, participants were immersed in a VE by means of an Oculus Quest 2 HMD (1832x1920px per eye and 89° FoV), with head and hand tracking directly provided by the headset. High-frequency tracking was activated to have 60Hz tracking. The VE was developed in Unity 2020.3.10f1. While the Oculus Quest 2 is an autonomous headset, it was wired to a laptop (Intel Core i7-8750H CPU and GTX 1070) to ensure optimal performance.

2.2.5 Experimental protocol

Participants had to fill and sign an informed consent form before having the experimental protocol explained to them. All participants were provided with the exact same written instructions, which indicated that they would have to perform three blocks of 5 minutes each, each block associated to a different movement type (either tapping, abducting/adducting the fingers or counting as in [Jeu+18] – in order to introduce variability in the experiment, without considering the movement type as an impacting factor). The *experimental* VE was a virtual room where participants were embodied in an avatar seated in

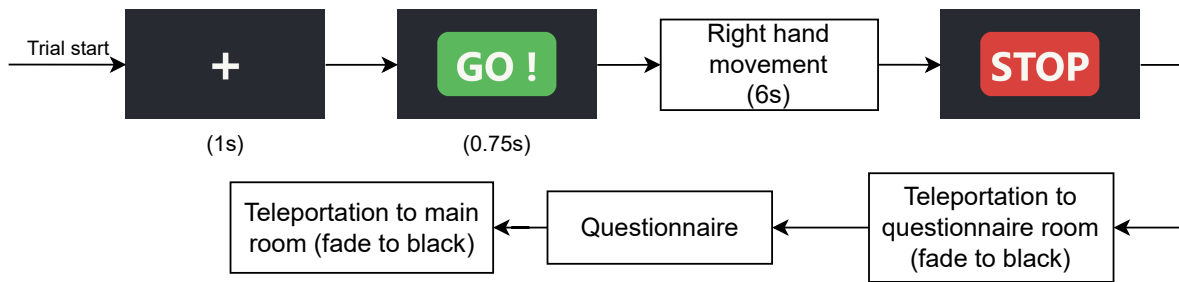


Figure 2.3 – Workflow of a trial. Participants had to repeat the movement, while looking at their virtual right-hand until a signal STOP was displayed 6s after the GO signal.

front of a table ($205cm \times 75cm \times 67cm$). In front of them, a TV hanged on the wall ($1.60m$ from the virtual body, $158cm \times 0.85cm$), on which videos and signals were displayed (see Figure 2.1). The experimental protocol is depicted in Figure 2.2.

After the explanation of the experiment, the VR headset was installed. The experiment first started by displaying videos of the different right-hand movements participants would have to perform. Participants could repeat them while the video was playing, and were corrected if the movement was done improperly. Then, participants had to perform a small tutorial of 3 trials (see next paragraph) in order to introduce them to the experimental protocol and to get used to the VE. Finally, once all remaining questions from the participants were answered by the experimenter, the experiment consisting of 3 blocks of 12 trials each started (see Figure 2.2 and 2.3).

Participants could take a break between blocks if they wanted to. On average, it took 40 minutes for each participant to complete the whole experiment (including explanations). In total, participants performed 36 trials ($3 \text{ blocks} \times 12 \text{ trials}$), resulting in 3 trials per condition. The movement associated with each block, as well as the order of the 12 conditions within a block were counterbalanced between the participants in order to avoid any order effect. The only fixed parameter was the first trial of each block being a “full embodiment” condition (*Synchronous* and *Anthropomorphic-hand* and *1PP*) to get a reference for other trials. This was necessary because of one of the agency manipulation (the thumb moving by itself). For the movement to be realistic, the movement of the thumb was recorded during this reference trial, which had to happen before the *Manipulated* condition.

The tutorial’s aim was to get the participants used to the SoSL manipulation, i.e changing the visuospatial perspective. Indeed, as trials are only 6s long, it could be unsettling for some people the first time in a third-person perspective. The tutorial consisted

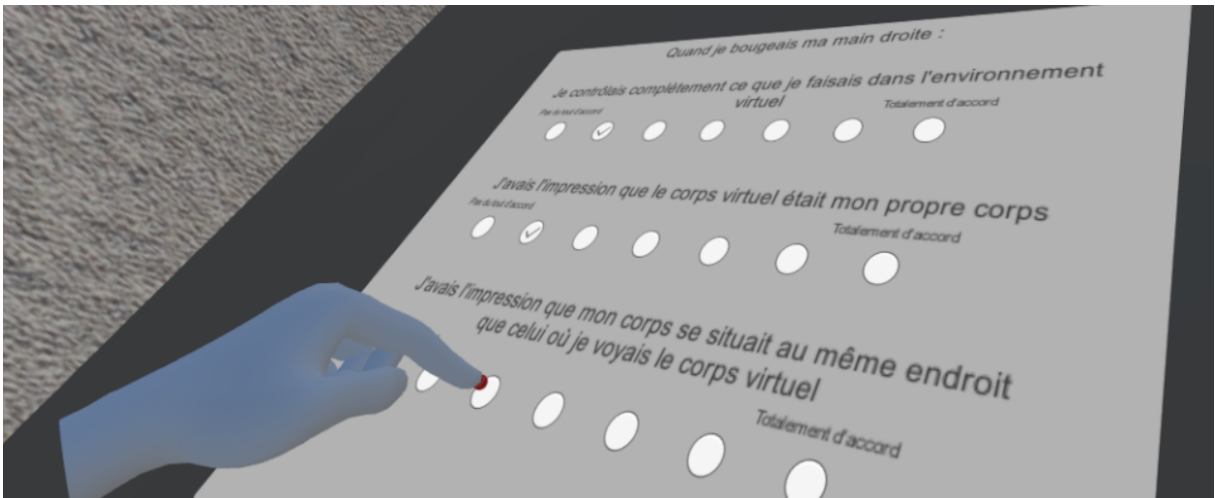


Figure 2.4 – Questionnaire being filled in VR with the left-hand using the standard Oculus hand representation and no avatar.

in 3 (non-recorded) predetermined trials using the tapping movement: the first trial was a “full embodiment” condition; the second trial was only altering the SoSL by putting participants in the *3PP-EP* condition; then a third trial in “full embodiment” again.

2.2.6 Subjective Measures

Most VR experiments about virtual embodiment use a questionnaire after each condition to assess the level of embodiment of the participant. Usually, the questionnaire is inspired from Botvinick and Cohen’s RHI experiment [BC98], but there are also questionnaires designed for the SoE [RL20; PG21]. These questionnaires usually contain multiple questions for each component of the SoE. Given the number of trials and conditions we wanted to test, it was impossible to have our participants fill-in this kind of questionnaire after each of the 12 conditions.

As a consequence, we followed the procedure used in Jeunet et al. [Jeu+18] to evaluate the SoE after each condition. After each trial, participants were asked to answer in VR 3 questions only, one to evaluate the SoA (“I was in full control of my actions in the virtual environment”), one to evaluate the SoSL (“I felt as if my body was located where I saw the virtual body”) and one to evaluate the SoBO (“I felt as if the virtual body was my body”). These questions were inspired or taken from existing questionnaires [BC98; Jeu+18; Hur+20; PG21]. The questions were preceded by “When I moved my right hand” to make sure participants rated their SoE during the hand movement only. For each

question, participants answered on a 7-point Likert scale from “Strongly disagree” to “Strongly agree” with no label in between.

Participants answered the questionnaire directly in VR, with their left hand, with only an Oculus hand appearing in the VE (and no avatar – see Figure 2.4 – and the Oculus left hand was never shifted regardless of the *SoSL-manipulation* level) as to not alter the feeling of the trial. Participants were asked to try to keep their right hand posture while answering the questionnaire to be ready to start for the next trial.

2.3 Results

Rstudio [RSt20] software was used to perform the statistical analyses and Python 3.8 was used to plot the figures with Seaborn/Matplotlib [Was21; Hun07]. The significance level used is $\alpha = 0.05$, corrected with Bonferroni methods.

Three 3-way ANOVAs for repeated measures were performed considering as factors *SoA-manipulation* (*Synchronous vs Manipulated*), *SoSL-manipulation* (*1PP vs 3PP-PP vs 3PP-EP*) and *SoBO-manipulation* (*Anthropomorphic-hand vs Stick-fingers*). The goal of these analyses was to investigate the relationships between one component of the SoE and the two others. For clarity, only significant and relevant results are reported. Full analyses data are available in Appendix A.

The 3 dependent variables were: the SoA score (s_soa), the SoSL score (s_sosl) and the SoBO score (s_sobo). For each of the 12 conditions, the score is defined as the mean of the 3 trials performed in this condition (1 per block). This ensures the assumption of independence of the ANOVA is met. Because the questionnaire and experimental design are similar to [Jeu+18], we performed the same analysis. In the end, for each participant, there are 3 SoE components \times 12 conditions = 36 scores.

2.3.1 Impact of the Experimental Manipulations on the SoA Score

In this analysis, the dependent variable was the average SoA score. The normality assumption was respected, based on the Shapiro-Wilk test performed on the residuals. However, according to Mauchly’s test, the sphericity assumption was violated for the *SoSL-manipulation* variable ($p = 0.010$). So, the Huynh-Feldt correction was applied to the degrees of freedom.

The ANOVA reveals a significant main effect of *SoA-manipulation* ($F(1, 46) = 360.48$; $p < 0.001$; $\eta_p^2 = 0.887$), *SoSL-manipulation* ($F(1.75, 80.35) = 4.96$; $p < 0.05$; $\eta_p^2 = 0.097$) and *SoBO-manipulation* ($F(1, 46) = 42.27$; $p < 0.001$; $\eta_p^2 = 0.479$) on the SoA score. Post-hoc tests indicate that the mean SoA score in *1PP* ($M = 4.395$; $SD = 1.643$) is significantly higher than in *3PP-EP* ($M = 4.092$; $SD = 1.498$) ($p < 0.05$). The *SoA-manipulation* \times *SoSL-manipulation* interaction is significant ($F(2, 92) = 4.73$; $p < 0.05$; $\eta_p^2 = 0.093$). Pairwise comparisons reveal a significant difference only in the *Synchronous* condition between *1PP* and *3PP-PP* ($t = 3.313$; $p < 0.05$) and between *1PP* and *3PP-EP* ($t = 3.932$; $p < 0.01$) (see Figure 2.5). The *SoA-manipulation* \times *SoBO-manipulation* interaction is also significant ($F(1, 46) = 27.45$; $p < 0.001$; $\eta_p^2 = 0.374$). Pairwise comparisons reveal a significant difference between *Anthropomorphic-hand* and *Stick-fingers* only in the *Synchronous* condition ($t = 7.562$; $p < 0.001$) (see Figure 2.6).

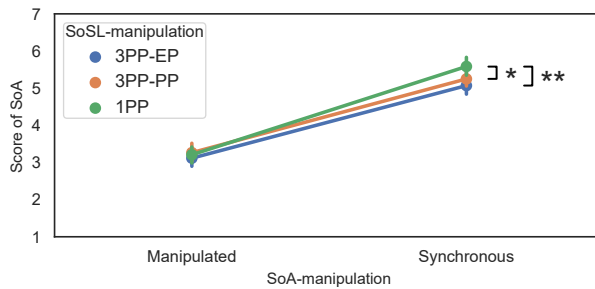


Figure 2.5 – Interaction between *SoA-manipulation* and *SoSL-manipulation* on the SoA score.

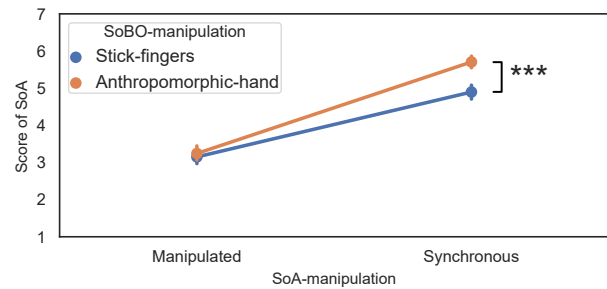


Figure 2.6 – Interaction between *SoA-manipulation* and *SoBO-manipulation* on the SoA score.

2.3.2 Impact of the Experimental Manipulations on the SoSL Score

The dependent variable in this ANOVA was the average SoSL score. A Shapiro-Wilk test revealed a violation of the assumption of normality of the residuals. Yet, these parametric methods are known for their robustness regarding non-normally distributed data when applied to Likert-scales [MA17; Nor10] which is why the data were not transformed and analysed as is. The sphericity assumption was violated according to Mauchly's test for the *SoSL-manipulation* ($p < 0.0001$) variable, *SoA-manipulation***SoSL-manipulation* ($p < 0.01$) and *SoBO-manipulation***SoSL-manipulation* ($p < 0.05$) interactions. Thus,

the degrees of freedom were corrected using the Huynh-Feldt correction.

The ANOVA revealed a significant main effect of *SoA-manipulation* ($F(1, 46) = 21.04$; $p < 0.001$; $\eta_p^2 = 0.314$), *SoSL-manipulation* ($F(1.45, 66.48) = 215.74$; $p < 0.001$; $\eta_p^2 = 0.824$) and *SoBO-manipulation* ($F(1, 46) = 14.30$; $p < 0.001$; $\eta_p^2 = 0.237$) on the SoSL score. Post-hoc tests indicate that the mean SoSL score in *1PP* ($M = 5.787$; $SD = 1.231$) is significantly higher than in *3PP-PP* ($M = 2.987$; $SD = 1.394$) which itself is significantly higher than in *3PP-EP* ($M = 2.036$; $SD = 1.276$) ($p < 0.001$). The *SoA-manipulation* \times *SoSL-manipulation* interaction is significant ($F(1.72, 79.25) = 5.29$; $p < 0.01$; $\eta_p^2 = 0.103$). Pairwise comparisons show a significant difference only in the *1PP* condition between *Synchronous* and *Manipulated* ($t = 5.989$; $p < 0.05$) (see Figure 2.7). The *SoSL-manipulation* \times *SoBO-manipulation* interaction is also significant ($F(1.82, 83.92) = 8.73$; $p < 0.001$; $\eta_p^2 = 0.159$). Pairwise comparisons reveal a significant difference between *Anthropomorphic-hand* and *Stick-fingers* only in the *1PP* condition ($t = 5.523$; $p < 0.001$) (see Figure 2.8).

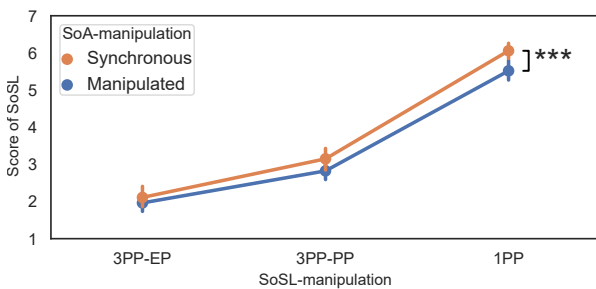


Figure 2.7 – Interaction between *SoA-manipulation* and *SoSL-manipulation* on the SoSL score.

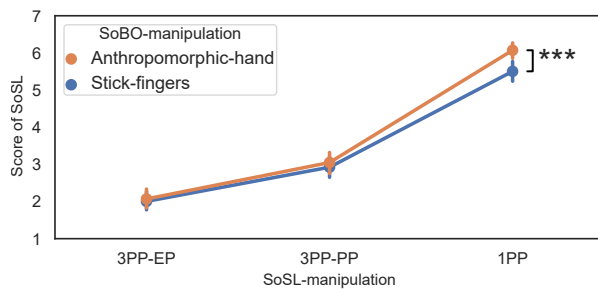


Figure 2.8 – Interaction between *SoSL-manipulation* and *SoBO-manipulation* on the SoSL score.

2.3.3 Impact of the Experimental Manipulations on the SoBO Score

Here, the dependent variable was the average SoBO score. A Shapiro-Wilk test revealed a violation of the assumption of normality of the residuals but as mentioned above ANOVAs are robust in our case (which is why the data were not transformed and analysed as is). According to Mauchly's test, the sphericity assumption was violated for the *SoSL-manipulation* variable ($p < 0.001$). Thus, the degree of freedom was corrected using the Huynh-Feldt correction.

The ANOVA revealed a significant main effect of *SoA-manipulation* ($F(1, 46) = 105.56$; $p < 0.001$; $\eta_p^2 = 0.696$), *SoSL-manipulation* ($F(1.54, 70.84) = 56.12$; $p < 0.001$; $\eta_p^2 = 0.550$) and *SoBO-manipulation* ($F(1, 46) = 96.69$; $p < 0.001$; $\eta_p^2 = 0.678$) on the SoBO score. Post-hoc tests indicate that the mean SoSL score in *1PP* ($M = 4.048$; $SD = 1.723$) is significantly higher than in *3PP-PP* ($M = 3.427$; $SD = 1.556$) which itself is significantly higher than in *3PP-EP* ($M = 3.066$; $SD = 1.517$) ($p < 0.001$). The *SoA-manipulation* \times *SoSL-manipulation* interaction is significant ($F(2, 92) = 6.56$; $p < 0.01$; $\eta_p^2 = 0.125$). The *SoA-manipulation* \times *SoBO-manipulation* interaction is also significant ($F(1, 46) = 24.29$; $p < 0.001$; $\eta_p^2 = 0.346$). Finally, the *SoA-manipulation* \times *SoSL-manipulation* \times *SoBO-manipulation* interaction is significant ($F(1.98, 91.15) = 3.24$; $p < 0.05$; $\eta_p^2 = 0.066$) (see Figure 2.9).

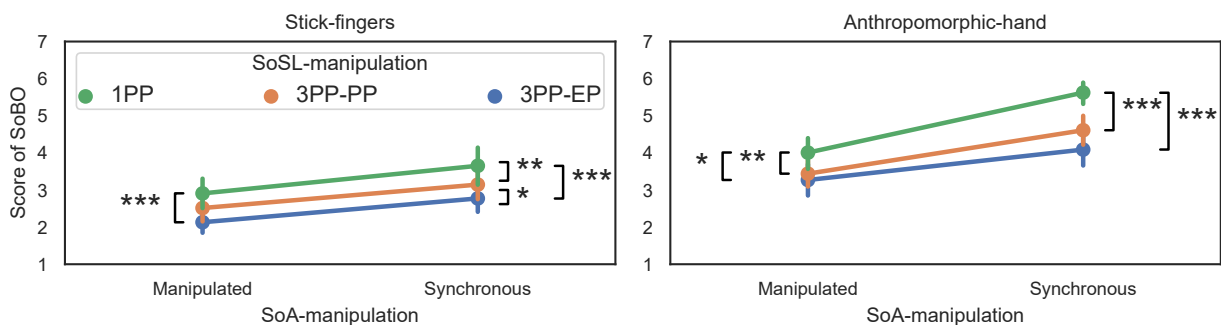


Figure 2.9 – Interaction between *SoA-manipulation*, *SoSL-manipulation* and *SoBO-manipulation* on the SoBO score.

2.4 Discussion

The aim of this study was to deepen the understanding of the SoE and the interactions between its components by 1) experimentally manipulating them in VR via a biased visual feedback, and 2) understanding to what extent each component can be selectively altered.

Participants' scores of SoA, SoSL and SoBO showed that all manipulations worked on their main target (i.e the *SoA-manipulation* impacted negatively the SoA, supporting hypothesis **H1**; the *SoSL-manipulation* impacted negatively the SoSL, supporting hypothesis **H6**; and the *SoBO-manipulation* impacted negatively the SoBO, supporting hypothesis **H8**). These results were expected, based on the literature, but we were able to confirm them in a different but similar experiment.

The experimental protocol failed to selectively alter each component. Nevertheless,

this study also brings new insight to the interaction between SoE components. Indeed, to the best of our knowledge, this is the first time that the SoA, the SoSL and the SoBO are manipulated in a same VR experiment to study their interactions. Results showed that the SoE components are tightly coupled.

2.4.1 Interaction between SoA and SoSL

Results revealed that the *SoA-manipulation* interacts with the *SoSL-manipulation* (see Figure 2.5 and Figure 2.7). These results contradicts **H3** and **H4**. Indeed, post-hoc tests showed that the *SoSL-manipulation* alters the user’s SoA but only in the *Synchronous* condition (with a large effect size). In the current study, it could be argued that in the *Manipulated* condition, the SoA may be too low for the *SoSL-manipulation* to have an effect. There were also no significant difference in the *Synchronous* condition between *3PP-PP* and *3PP-EP*, so shifting the user’s point of view by just 20 cm to the right might be already enough to alter the SoA. Likewise, results revealed that the *SoA-manipulation* has an effect on participants’ SoSL only in *1PP* condition. This again could be explained by the fact that in the *3PP-PP* and *3PP-EP* conditions, the SoSL may be too low to be impacted by the *SoA-manipulation*.

2.4.2 Interaction between SoA and SoBO

Interaction analysis and post-hoc tests showed that the *SoA-manipulation* interacts with the *SoBO-manipulation* (see Figure 2.6). This contradicts hypothesis **H2** but supports hypothesis **H7**. Indeed, we expected the *SoBO-manipulation* to not alter the user’s SoA, but this occurred in the *Synchronous* condition (with a large effect size). This is coherent with [Che+18]’s results stating that the relationship between the SoA and the SoBO may vary depending on the experimental conditions. Like previously, this could be explained by the fact that in the *Manipulated* condition, the SoA score is already too low for the *SoBO-manipulation* to have an effect. Bottom-up factors might have a stronger effect than top-down factors: the *SoBO-manipulation* targets cognitive processes while the *SoA-manipulation* leads to incongruent stimuli at the perceptual level (the visual cues do not match the perceptual cues produced by the actual movement) [LW22]. Likewise, results revealed the *SoA-manipulation* has an effect on participants’ SoBO score with a large effect size, supporting **H7**. These results reinforce the idea that the SoBO and SoA are dependent.

2.4.3 Interaction between SoBO and SoSL

Interaction analysis and post-hoc tests showed that the *SoBO-manipulation* interacts with the *SoSL-manipulation*. We hypothesised that the *SoSL-manipulation* would impact the SoBO score only in *3PP-EP* (**H9**). Results showed that the *SoBO-manipulation* altered the user’s SoSL, but only in the *1PP* condition, which contradicts hypothesis **H5**. We also expected to find the same results as in Maselli and Slater’s experiment [MS14] with hypothesis **H9** but it was not the case. While there is difference between *1PP* and *3PP-EP*, we also observed a difference between *1PP* and *3PP-PP* in all conditions except on *Stick-fingers+Manipulated* condition, and thus we do not replicate [MS14]’s results. This could be due to a difference in the experimental protocol and more specifically a different embodiment phase. In our case, visuomotor synchrony was used to elicit body ownership, whereas Maselli and Slater used visuotactile synchrony. Also, the duration of exposure is longer in their experiment. Also, the assessment of virtual embodiment is different as well because they used a 12-item questionnaire (compared to 3).

2.4.4 Limitations

Despite being the first VR experiment where the SoA, SoSL and SoBO are manipulated at the same time to study their interactions (to the best of our knowledge), our study has some limitations.

In this experiment, we used a non-anthropomorphic hand (the *Stick-fingers* condition) with five aligned stick fingers (i.e. without a thumb) instead of a robotic hand [LJ16] or a wooden block [LJ16] to alter the hand realism, because we needed hand and finger movements. Since this kind of hand has, to the best of our knowledge, not been used before, we do not know how it impacts the SoA. This hand could be perceived as inaccurate due to the incorrect position of the thumb, which could influence the SoA. However, it is still unclear how the SoA is impacted by hand appearance, as sometimes it was shown to have an impact [Arg+16] and sometimes not [LJ16]. We cannot conclude if the influence of hand realism on SoA in our experiment is due to the hand appearance or to the sticky fingers looking inaccurate. Nevertheless, the movements were not meant to be perfectly executed and we believe that this “sticky thumb” is not the cause of the impact of realism on the SoA. In most post-experiment verbal reports, participants indicated to be disturbed more by SoA manipulations even in the Stick-Fingers condition than by the hand realism. It remains an open question for future work.

Another limitation of this study is the short amount of exposure time. Indeed, each trial was only 6s long. It can thus be questioned if there were any sort of embodiment experienced by participants. With so many conditions, it was not feasible to have long exposition time for each condition with some repetitions, this is why we followed [Jeu+18]’s experimental design. Participants however had to perform a tutorial first, in which they could get used to the virtual body and the hand tracking system. Moreover, in post experiment verbal reports, participants mostly reported to feel embodied during the experiment. Also, all manipulations relied on visual feedback, so participants could perceive the differences directly. More generally, the impact of embodiment time in an avatar is still poorly studied in the literature. We know from Botvinick and Cohen’s RHI [BC98] that the longer the exposure, the stronger the ownership, but this remains to be replicated and studied in VR. Kocur et al. [KRS20] have proposed a protocol to study this and their results could help improve this experimental protocol.

The use of the Oculus left hand to fill the questionnaire after each trial may have impacted the SoE. However, the questionnaire explicitly mentioned “When I moved my right hand” to make sure participants rated their SoE during the hand movement only, and this was insisted on during the explanation of the experiment.

Finally, as mentioned in subsection 2.2.6, we could not use standardised SoE questionnaires [RL20; PG21] after each condition, and relied on the method used in [Jeu+18]’s experiment. This makes comparability with other experiments harder and the SoE scores reliability cannot be assessed. However, our questions were taken from existing validated questionnaires, and more importantly, in this within-subject experiment we were more interested in differences between the conditions to better understand the interactions between the components. Further experiments should explore other experimental designs in order to include these standardised questionnaires. A questionnaire is being designed by Eubanks et al. [Eub+21], which aims to be usable in VR and short (7 questions in its preliminary version). This could be a good alternative in the case of our experiment.

2.5 Conclusion

The presented experiment explored the relationships and interactions between the SoA, the SoSL and the SoBO. We were able to confirm previous results like the link between SoA/SoBO and SoBO/SoSL. Moreover, we observed that the SoSL and SoA seem to be not independent, and this is, we believe, the first experiment investigating the

link between the SoSL and the SoA in VR scenarios. Finally, we confirmed that the three components are all inter-related regarding the SoBO score. Nevertheless, additional studies are required to explore the relationship between the components and better understanding the factors impacting them.

NEUROPHYSIOLOGICAL MARKERS OF THE SENSE OF AGENCY

Abstract: The sense of agency is a construct of utmost importance from both an individual and a social perspective, as it rules the sense of responsibility that we have regarding our own actions. Yet, it can be altered, for instance due to clinical conditions (e.g., dissociative disorders) or when a technology does not respond as expected to our commands. In this chapter, our objective was to assess the extent to which alterations of agency (AoA) could be monitored during different natural hand movements using surface EEG, which is compatible with out-of-the lab measurements (e.g., for clinical assessment or technology evaluation). We analysed EEG data (N=24) collected using a validated Virtual Reality protocol that enables inducing AoA by distorting the visual feedback provided to participants during natural right-hand movements. While single-trial classification analyses were not conclusive, we were able to identify different EEG modulations that could reflect AoA. First, an N200 was elicited in Manipulated condition only (where the sense of agency (SoA) is manipulated). Second, in contrast with Synchronous condition (where the VR movement of the user is not manipulated), Manipulated condition was characterised by θ power decrease over the sensorimotor and parieto-occipital areas at early stages of the trials (0-500ms) followed by an increase over the right temporo-parietal areas (500-1000ms).

3.1 Introduction

In the introduction, we presented our research questions. In this chapter, the focus is on **Q2: “Are there neurophysiological markers of each component of the sense of embodiment (SoE) that can be measured in real-time in a VR use case scenario?”**. To tackle this question, it is more relevant to study the SoE separately, one component at a time. Following the user study presented in chapter 2, our objective was

to perform the same study using EEG to find neurophysiological markers of the SoE, once the experimental protocol has been validated. However, Jeunet et al. [Jeu+18] performed a VR experiment that consisted in manipulating the participants' sense of agency (SoA) in which they measured participants' EEG activity. These EEG signals were not fully analysed, so we decided to do further analysis on these data. In this chapter, we thus focus on answering partly **Q2**, focusing on the SoA.

As presented in chapter 1, the SoA is defined as “the experience of controlling one’s own actions, and, through them, events in the outside world” [HC12]. The SoA is a construct of utmost importance, both from an individual and a social perspective as it rules the sense of responsibility that we have regarding our own actions [HC12]. Yet, in some circumstances, it can be altered. Specific psychiatric conditions such as dissociative disorders, e.g., depersonalisation and derealisation, as well as depression are associated with abnormal SoA resulting in patients feeling that external agents control their own actions [HC12; Rab+18]. Neurological diseases such as disorders of body awareness can also result in dysfunctional SoA. In the motor alien hand syndrome, for example, involuntary and apparently autonomous purposeful movements of the affected hand occur, despite what patients report verbally to be their intention [PHR19].

Beyond such clinical conditions, each one of us can be confronted to alterations of agency (AoA) in our daily life, especially when we interact with a technology that does not respond as expected to our commands [Moo16]. AoA can result in a decreased motivation and engagement in the task [Kar+16] that may in turn have detrimental effects on general learning mechanisms. In the context of VR, this eventually leads to reduced efficiency of training and therapies. Deepening our understanding of the cognitive, behavioural and neurophysiological bases of AoA is thus essential, both from basic knowledge and application perspectives, whether it is to improve clinical diagnosis, rehabilitation procedures or to enhance VR in healthy people. To understand the impact of AoA in everyday life, we need to be able to characterise and monitor AoA from multiple perspectives, multiple methods and tasks, including lab environments, but it is also crucial in ecological out-of-the-lab settings. Yet, as stated in chapter 1 the SoA is “phenomenologically thin” and therefore difficult to measure, especially in non-controlled environments [Hag05; HC12].

In this chapter, our main objective is to assess the extent to which the SoA and its alterations could be monitored during natural hand movements that resemble the kind of tasks that would be performed out-of-the-lab in VR or in clinical contexts. The development of novel experimental paradigms for evaluating the SoA while manipulating

AoA not only helps advance the understanding of the concepts such as depersonalisation or the loss of SoA in various clinical disorders, but contributes to the understanding of the agency attribution toward our action for everyday life. It could thus potentially be used in therapies in which patients are exposed to experimentally-induced SoA experiences in a safe environment [Ren+10].

We presented in chapter 1 the comparator model [DNV08]. Another process also relevant to AoA is action monitoring, that is domain-general, and may contribute to the judgement component part of the SoA, but which has been, to this date, less explored in this context. Frontal-midline θ activity is suggested as neural activity monitoring one's actions and the external environment for incongruencies, conflicts and errors, to initiate rapid and flexible behavioural adjustments [CZA12; CS15]. Such cognitive control processes are associated with θ generator in the medial frontal cortex, including the midcingulate cortex and supplement motor areas, and include fronto-cingular-parietal networks [Coo+15]. A specialised microcircuit in medial frontal cortex has been suggested to implement the neurophysiological mechanisms of cognitive computations of conflict detection, processing and broadcasting to other brain regions via θ oscillations [Coh14]. Frontal-midline θ falls into the time range of the N200 and P300¹ [Hus+13], whereby the N200 seems to mirror θ band activity [NIS11] and has been associated specifically to conflict processing in contrast to the P300 [Enr+10].

The advantage of neuroimaging methods is that they enable a direct, specific and real-time assessment of AoA. Among them, surface EEG seems to be the most relevant to assess AoA in clinical and VR *out-of-the-lab* contexts as it enables the mobility of the device, is movement-tolerant, inconspicuous and comfortable, and therefore does not interfere with daily life activities [Bat+17]. Yet, only a few studies relied on this technique to measure AoA so far in VR and, most importantly, these studies have been performed in very controlled lab experiments, which are far removed from common clinical or VR tasks. With this study, we demonstrate EEG measurements of AoA in a better ecological contexts using VR.

To do so, we used data collected in a VR-based context [Jeu+18] that consisted in manipulating the participants' SoA while they were performing natural movements of the right hand through the distortion of the VR visual feedback. Indeed, for a positive JoA to occur, the action outcome, or feedback, must comply with three principles as explained

1. These indicates electrical signals produced by the brain in response to an external stimulus some milliseconds after the stimulus. "Nxxx" is for "negative" meaning the potential is decreasing (respectively "Pxxx" is for "positive" meaning the potential is increasing) after *xxx* ms.

in chapter 1 [WW99]: the *priority* principle, the *consistency* principle and the *exclusivity* principle. The experimental setup and protocol will be detailed in subsection 3.2.1.

As explained previously, in the current chapter, we aim at understanding the neurophysiological correlates of AoA and therefore focus on EEG data analyses. We show that AoA elicited during natural hand movements using VR are characterised by specific modulations of both oscillatory activity and event-related potentials (ERPs), that are detectable using surface EEG. Additionally, we try to model a classifier to detect in a single-trial fashion these modulations of the EEG activity. This could allow for a better evaluation of the SoA in VR.

This chapter is structured as follows. Section 3.2 presents the experimental protocol and design of Jeunet et al. [Jeu+18] as well as our research hypotheses. Our results are analysed in Section 3.3 and discussed in Section 3.4. Finally, Section 3.5 concludes this work.

3.2 Material and Methods

In this section, we first present the experiment on which the study is based (Jeunet et al. [Jeu+18]) then we detail our research hypotheses.

3.2.1 Experiment of Jeunet et al.

The aim of Jeunet et al.'s [Jeu+18] study was to validate the protocol, i.e., to assess its efficiency to induce AoA. Here, we complement that paper by thoroughly analysing the associated EEG data.

Participants

Twenty-four (24) participants were recruited in the experiment (5 women, 19 men, 23.54 ± 2.84 year-old (mean \pm SD)). The study was conformed to the Declaration of Helsinki and approved by the local ethical committee (authorisation number: 2017-019/01). All the participants signed an informed consent form. Furthermore, they were all right-handed based on the Harris test of lateral dominance [Har57].

Experimental Manipulation of the Sense of Agency

In this experiment, the SoA is manipulated by means of biased visual feedback (the outcome of an action does not match the intended action), following either

- the priority principle: a temporal lag (of 1, 1.5 or 2s) was added to the movement of the participant;
- the consistency principle: two fingers are inverted (index/ring, index/little finger or middle/little finger);
- or the exclusivity principle: a “mad” finger (thumb, middle or little finger) moves randomly.

Variability was inserted inside each manipulation type in order to avoid redundancy and habituation so that participants could not predict the amount of lag, the fingers being inverted or which finger moves randomly. Nevertheless, these variations are not distinguished in the analysis as all were found to efficiently manipulate the users’ SoA [Jeu+18]. Finally, in this experiment, there are two agency conditions:

- *Synchronous* condition, where there is no manipulation on participant’s hand tracking (direct mapping from the user’s real hand to the avatar’s hand);
- *Manipulated* condition, where the VR feedback of the participant’s hand movement is biased by one of the three aforementioned manipulations.

Movement types

In this experiment, participants had to perform three different hand movement (see Figure 3.1):

- *tapping*: tapping with fingers from the thumb to the little finger;
- *counting*: counting with fingers from 1 to 5, starting with the fist closed;
- *abduction/adduction*: adducting and abducting horizontally the fingers.

In Jeunet’s et al. experiment, these movements were introduced to be more representative of “natural” finger movements in the experiment and prevent habituation, and thus were not considered as a factor. In this chapter and our analyses however, we will consider the *MovementType* as a factor (more details in the next sections).

Apparatus

In this experiment, participants were immersed in the VE by means of an Oculus Rift (DK2) HMD, which has a resolution of 960x1080px per eye and a 100° vertical FoV



Figure 3.1 – Participant performing different hand movements. The first three photos represent the three movements (tapping, counting, adduction). The right photo shows a participant performing a movement and the VR feedback as displayed in the participant’s HMD. Figure from Jeunet et al.

/ 90° horizontal FoV. The experiment was implemented in Unreal Engine 4.15.3 using both C++ and blueprints. The graphics were generated by a desktop computer (Intel Xeon E5-1603 v4 CPU and GTX 1080), ensuring a constant 75Hz display rate during the experiment. Participant’s hand tracking was provided by a Leap Motion. The Leap Motion was placed on the Oculus Rift using the Leap Motion Universal VR Developer Mount, allowing a permanent interaction space in front of the head of the participant, even when they moved their head. The environment in front of the participant was covered by an anti-reflective tissue to limit infra-red interferences and ensure optimal tracking. The VR apparatus was supported by an articulated arm in order to prevent it from applying pressure on the EEG electrodes.

EEG was recorded using two g.USBamp amplifiers (g.tec, Austria), by means of 32 wet (g.tec LadyBird) scalp electrodes (C6, CP5, CP1, CP2, CP6, P7, P5, P3, Pz, P4, P6, P8, PO7, PO3, PO4, PO8, F5, F1, F2, F6, FC5, FC3, FC1, FC2, FC4, FC6, C5, C3, C1, Cz, C2, C4, 10-20 system; see Figure 3.3), referenced to the right ear and grounded to AFz. Data was recorded using OpenViBE [Ren+10].

The experimental set-up is shown in Figure 3.2.

Experimental protocol

The objective of [Jeu+18] was to validate the protocol, i.e., to assess its efficiency to induce AoA. All participants were provided with the exact same written instructions, which indicated them that they would have to perform three runs of 12 minutes each.

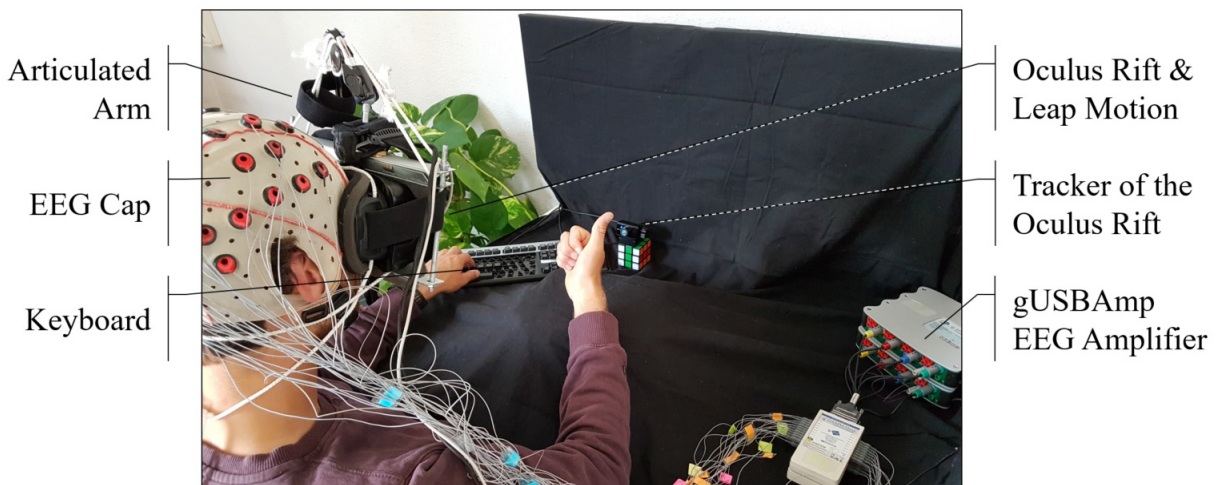


Figure 3.2 – Experimental setup used in Jeunet et al. [Jeu+18]. Participants wore an EEG headset and were immersed in a virtual environment with an Oculus Rift attached to an articulated arm. Participant’s right hand was tracked by a Leap Motion fixed on top on the Oculus Rift. Figure from Jeunet et al.

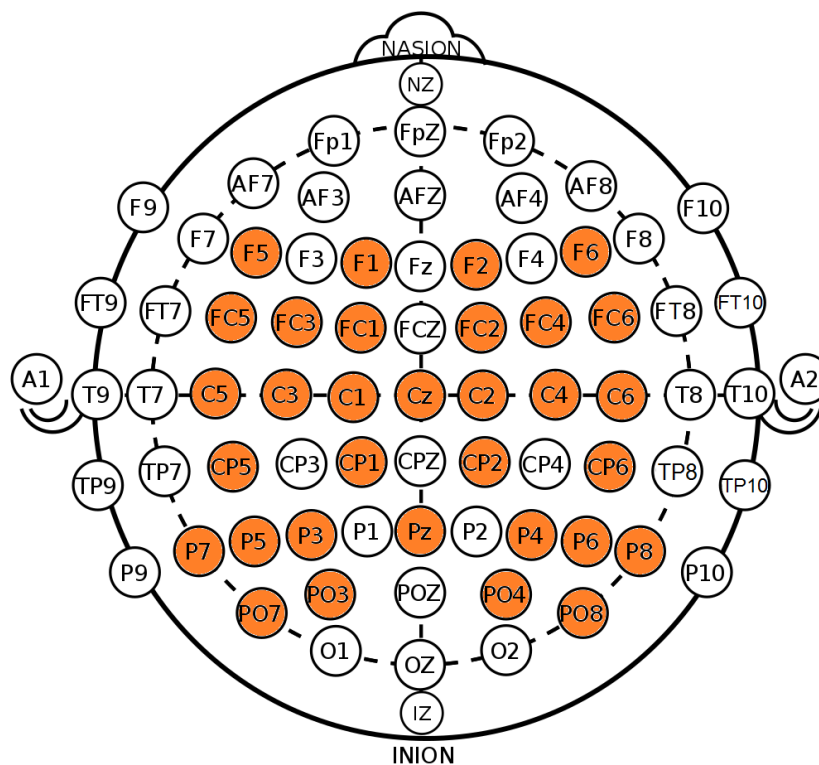


Figure 3.3 – EEG channels used in Jeunet et al. [Jeu+18], represented on the 10-20 system for EEG electrode placement. Used EEG channels are coloured in orange.

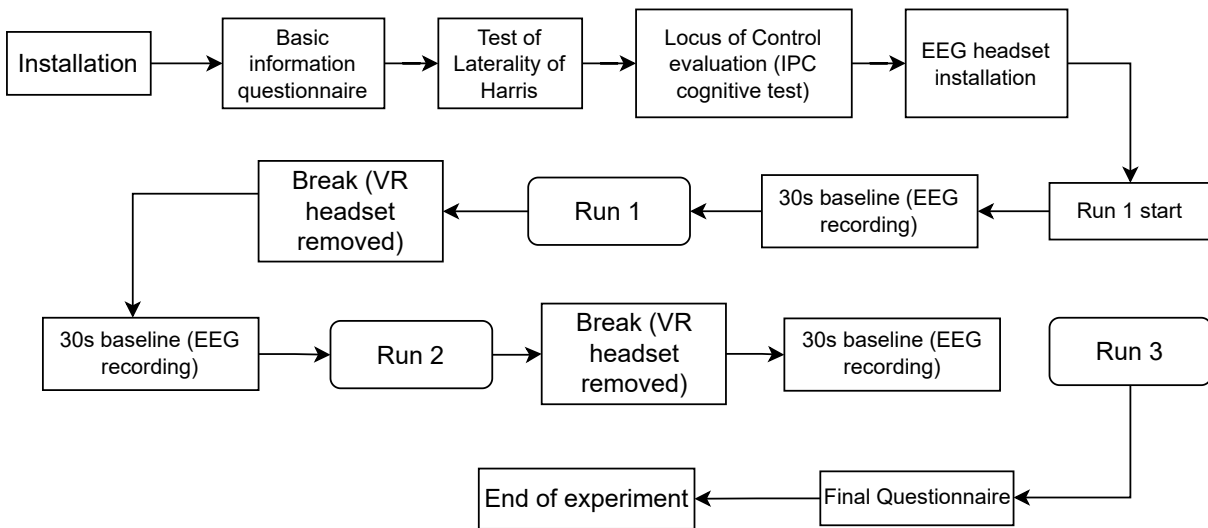


Figure 3.4 – Experimental protocol in Jeunet et al. [Jeu+18].

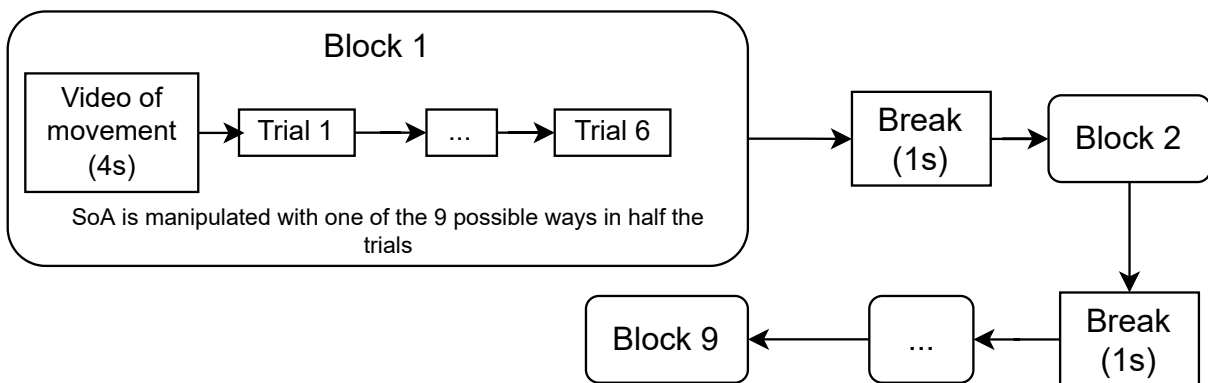


Figure 3.5 – Workflow of a run, constituted of 9 blocks of 6 trials. Movements as well as order of the conditions are counter-balanced between the blocks in order to avoid any order effect. The only constant trial is the first trial of each block, which is always a *Synchronous* trial.

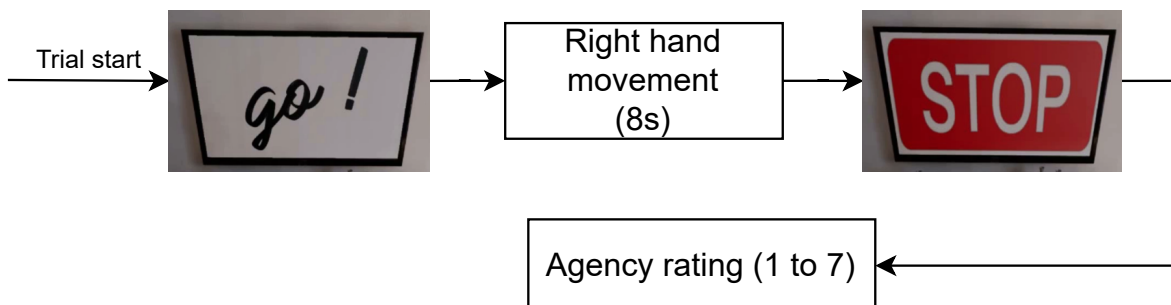


Figure 3.6 – Workflow of a trial. Participants had to repeat the movement, while looking at their virtual right-hand until a signal STOP was displayed 8s after the GO signal.

In this task, participants were immersed in a virtual living room which was equipped with a TV on which some pictures and videos would be displayed. Crucially, a table was displayed on which the virtual hand of their avatar would be placed. The experimental protocol is depicted in Figure 3.4, Figure 3.5 and Figure 3.6. Each of the experimental run started with a 30s-long baseline, and was then divided into nine blocks of trials. Each block of trials started with a four second-long video that was displayed on the virtual TV. It was used to instruct participants about which movement they should perform. Following this video, participants had to perform the demonstrated movement repeatedly for six trials of eight seconds each. Each trial started with a “Go” picture displayed on the virtual TV. After eight seconds, a “STOP” picture informed the participants they could stop performing the movement, and the following question was asked: “On a scale ranging from 1 to 7, how much did you feel in control during this trial?”. These subjective ratings were used in [Jeu+18] to validate the efficiency of the protocol to induce perceived AoA. To answer, participants had to press the appropriate key (between 1 and 7) on the keyboard with their left hand and then to validate by pressing the space bar. The next block of trials started 1s afterwards. Among the six trials of each block, three were associated with the *Synchronous* condition, while the other 3 were associated with *Manipulated* condition. In the *Synchronous* trials, the VR feedback fitted the movements being performed by the participants. During the *Manipulated* trials however, the feedback was biased following either the priority, consistency or exclusivity principle, as explained previously. Thus, each participant took part in $3 \times 9 \times 6 = 162$ trials, half ($N=81$) in each of the *Synchronous* and *Manipulated* conditions. The movement types were balanced over conditions with $N=27$ trials of each movement per condition. In the *Manipulated* condition, the manipulation types and modalities were also balanced over the different movements. In addition, the order of the manipulation conditions and their modalities were pseudo-randomly counterbalanced over the runs, blocks and participants in order to avoid order effects. Finally, all participants completed the internal, powerful others and chance (IPC) locus of control (LoC) questionnaire [Lev73] (see details below).

Measures

In this experiment, participants rated their level of agency at the end of each trial. This was used to evaluate the SoA of participants and validate the experimental protocol. In addition to this questionnaire, the EEG activity of participants was recorded during the whole experiment, starting with a 30s-long baseline. Finally, participants’ LoC was

measured with the IPC cognitive test [Lev73] in order to investigate its relationship with the SoA. The LoC is the extent to which individuals believe they have control over how events in their lives will turn out as opposed to outside circumstances (beyond their power).

3.2.2 Design and hypotheses

Jeunet et al.'s [Jeu+18] experiment followed a full factorial 2×3 design : *SoA-Manipulation* (*Synchronous* vs *Manipulated*) and *MovementType* (*tapping* vs *counting* vs *abduction/adduction*). All variables were within-subject.

In this section, we define our working hypotheses on the EEG analyses that will be presented in this chapter (and not the hypotheses of Jeunet et al.). The goal was to see if it is possible to measure AoA induced in VR by means of biased visual feedback using surface EEG. In addition to the two factors presented, we defined the *Locus* between-subject factor (*LoC-high* vs *LoC-low*), separated based on the group median. Brain EEG activity can be characterised either in the temporal or spatial domain. We declined two hypotheses, suggested by the literature.

Sensory attenuation is known to be reflected by a decreased amplitude of the N100 component of the EEG ERP [GS11; HDW13]. This early ERP component would then be an indicator of the pre-reflective feeling of agency [Dav12]. On the other hand, the amplitude of the P3a component² seems to positively correlate with judgement of agency ratings [Küh+11], even though judgement of agency takes much longer than 300ms to be consciously computed. As stated by David [Dav12], these results suggest that “both levels of agency [*namely the FoA and JoA*] are better characterised by early predictive processes”. A first hypothesis, regarding temporal analysis of EEG, is then:

- H1** An N100, N200 and a P300 components are present over the sensorimotor cortex, in the *Manipulated* condition only, as conflict detection falls into the time range of the N200 and P300[Coh14] and sensory attenuation is reflected by an N100 [GS11; HDW13];

An increased activity in the supplementary motor area (SMA) has been shown to characterise agency [FF02; KBH13]. It has also been demonstrated that an increase of the activity of the anterior insula occurred when a person was aware of causing an action [FF02]. Contrarily, the activation of the posterior parietal cortex (PPC) seems to

2. Also called novelty P3, it peaks at 250-280ms and is located in fronto-central areas. It is triggered as a response to a new *unexpected* event.

negatively correlate with the SoA [FF02]. In other words, the activity in the PPC, and particularly in the angular gyrus, increases when a mismatch between the predicted and the actual sensory outcomes of the action occurs [Cha+13]. Similarly, from the comparator model perspective, the PPC has been found to be involved in the SoA, because the PPC is involved in the detection of visual-motor mismatches [Far+03; Far+08]. Nonetheless, these correlates are still discussed. For instance, no correlation between PPC activation and subjective measures of agency was reported in Kuhn et al. [KBH13]. As stated in the introduction, frontal-midline θ activity is suggested as neural activity monitoring one’s actions and the external environment for incongruencies, conflicts and errors, to initiate rapid and flexible behavioural adjustments [CZA12; CS15]. A second hypothesis, regarding spatial analysis of EEG, is then:

H2 Higher θ activity in *Manipulated* than in *Synchronous* reflecting conflict monitoring processes [CS15; Coh14].

To summarise, we expect to detect brain activity related to the SoA in the sensorimotor cortex in the θ frequency range (4-8Hz) and the presence of an N100, an N200 and a P3a component.

Finally, as an exploratory analysis, we wanted to examine the link between the SoA as measured with EEG and the participants’ LoC. Indeed, Jeunet et al. [Jeu+18] found a positive correlation of the LoC with the perceived SoA score in *Manipulated* trials, as measured with their questionnaire. We want to know if the same results apply to the EEG data or not.

3.3 Results

EEG data was pre-processed and analysed using Matlab with the EEGLab toolbox [DM04]. The significance level used is $\alpha = 0.05$, corrected with false discovery rate (FDR) methods.

3.3.1 EEG preprocessing

We preprocessed offline the EEG data sampled at 512 Hz, using a Notch filter at 50Hz and a band-pass filter in 1-40Hz before epoching. Epochs³ started 1000ms before the movement signal was given (“Go” signal) and ended 8000ms after the start of the signal.

3. Epochs are specific time-windows extracted from the continuous EEG signal. In our study, they are time-locked to the “Go” signal, that means the “Go” occurred at $t = 0s$ of each epoch.

An automatic artefact rejection method was then used: epochs containing outliers (outside of the $[-200\mu V; 200\mu V]$ range) or abnormal trends (slope greater than $200\mu V$ with a R-squared limit fixed to 0.3) were rejected. More epochs were rejected based on joint probability and kurtosis of activity (local and global threshold of 10 standard deviations (SDs) from mean value) [Luc14]. Finally a manual visual inspection was performed to reject remaining trials with artefacts. Following that, noisy channels were rejected automatically based on kurtosis with a threshold of 30 SD from mean value. Removed channels were interpolated with spherical interpolation. Finally, EEG data was re-referenced using Common Average Referencing (CAR).

3.3.2 Statistical analyses

Two types of non-parametric permutation-based ANOVAs were performed (10,000 permutations). The first type considered as factors *SoA-Manipulation* (*Synchronous vs Manipulated*) and *MovementType* (*tapping vs counting vs abduction/adduction*). The second type considered as factors *SoA-Manipulation* and *Locus* (*LoC-high vs LoC-low*). The goal of these analyses was to investigate how EEG activity was modulated by the factors of investigation. The EEG signal can be analysed either in the time domain (amplitude over time) by studying ERP averages or in the spatial domain (magnitude of spectral power in a particular frequency range).

Event-related potential analyses

In these analyses, the dependent variable was the mean EEG epoch over trials and participants. The analyses were performed on each epoch time-sample (to analyse the EEG activity over time; at 512Hz leading to 512 samples in a 1s-length epoch). Each channel was processed independently, meaning that in total 32 channels \times 512 samples ANOVAs were performed.

ERP analyses over the medial frontal cortex enabled us to investigate the extent to which the SoA neuromarkers depicted in the literature [GS11; Küh+11; HDW13] could be measured in less controlled, more natural motor tasks using surface EEG. The task led to an N100, N200 and P300 (see Figure 3.7).

We found no *SoA-Manipulation***MovementType* interaction effect and no main effect of *MovementType*, but a main effect of *SoA-Manipulation*. Indeed, results in C1 (i.e., in regard of the left sensorimotor cortex) showed a N100 deflection. Although the N100

deflection over C1 was larger in *Manipulated* than in *Synchronous* condition, this did not result into statistical significance [$.07 \leq p \leq .08$ between 115 and 140ms, $Mean_{p-adj}=.077$; peak of significance ~ 130 ms]. Differences between the ERPs of both conditions are however significant between 275 and 350ms [$.001 \leq p \leq .04$ between 275 and 350ms]. An N200 appears in the *Manipulated* condition only⁴. Additionally, a P300 latency shift and amplitude difference between the conditions can be observed as well.

We also analysed the impact of the participants' personality on EEG oscillations. This analysis revealed no main effect of *Locus* condition nor *SoA-Manipulation*Locus* interaction. However, as previously, a main effect of the *SoA-Manipulation* was noted [$.01 \leq p \leq .04$ between 300 and 335ms, $Mean_{p-adj}=.02$; peak of significance ~ 320 ms].

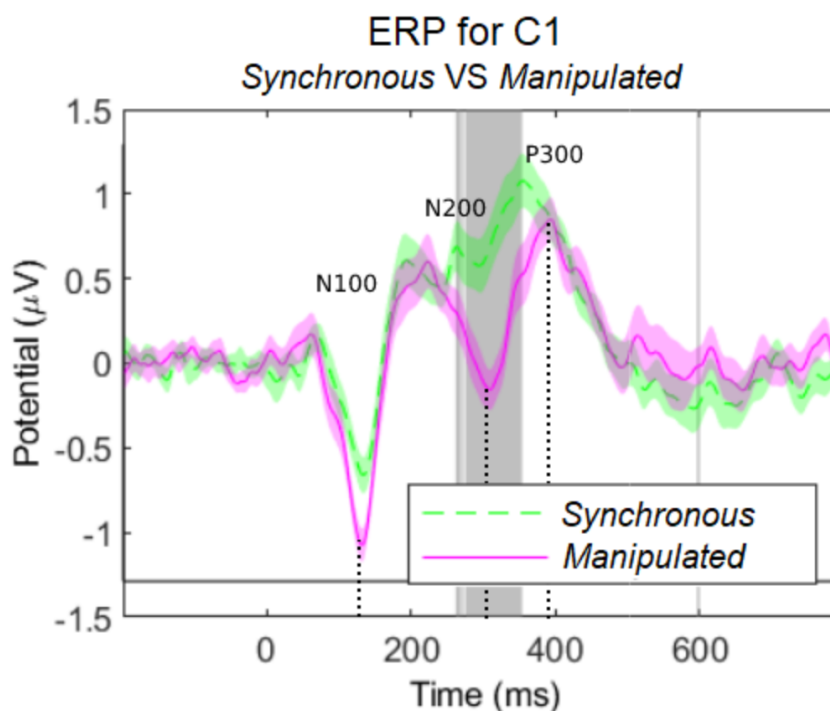


Figure 3.7 – Average ERP of all participants in C1 electrode compared between *Synchronous* and *Manipulated* conditions. We can observe the task led to an N100, N200 and P300. Grey areas represent zones where the time samples are significantly different ($p < 0.05$).

4. Note that the N200 appears after 200ms, that might be due to inter-subject variations.

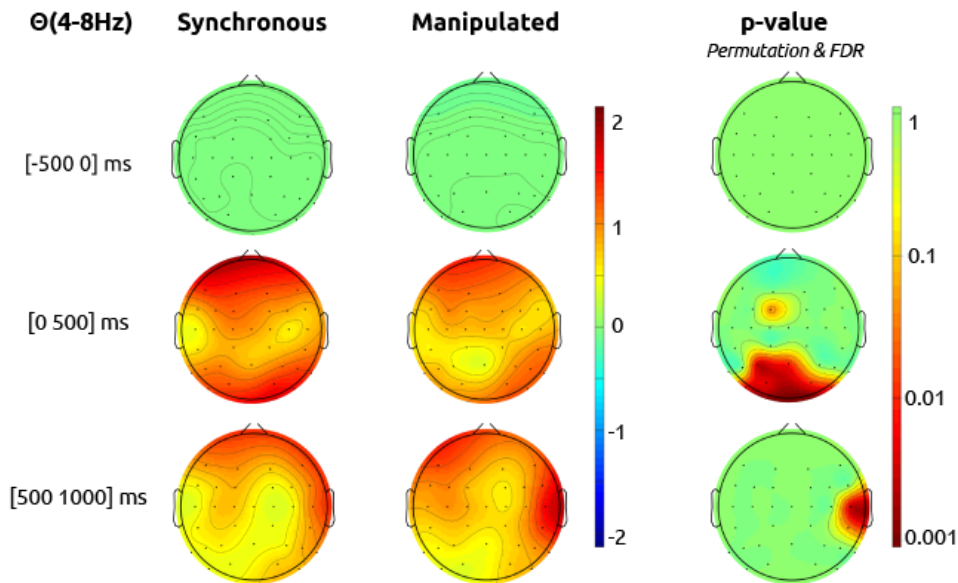


Figure 3.8 – Topography plots of spectral power in θ band in both conditions compared to the baseline in different time range: (top) baseline time range (-500ms to 0ms); (middle) 0-500ms range; (bottom) 500-1000ms range.

Spectral power analyses

In these analyses, the dependent variable was the EEG spectral power in the θ frequency band (4-8Hz) over trials and participants, averaged over a certain time-window. The analyses were performed over three different time windows: [-500;0]ms (baseline), [0;500]ms (beginning of the trial, which would relate to the FoA) and [500;1000]ms (feedback processing after the “Go” signal, which would relate to the JoA). Each channel was processed independently, meaning that in total 32 channels \times 3 time windows non-parametric permutation-based ANOVAs were performed.

The literature on conflict monitoring suggests that the perception of inconsistencies between actions and their outcomes is underlain by modifications in θ oscillations [CZA12; CS15], this is why we selected the θ frequency range. Results revealed no main effect of *MovementType*, *Locus* nor *SoA-Manipulation* \times *MovementType* and *SoA-Manipulation* \times *Locus* interactions. However, a main effect of *SoA-Manipulation* appeared: i) between 0 and 500ms, mainly over the parieto-occipital areas [$.001 \leq p \leq .01$ in P3, Pz, PO7, PO3, PO4, PO8], ii) between 500 and 1000ms over the right parieto-temporo-central areas [$p=.01$ in C6; $p=.03$ in CP6].

3.3.3 Single-trial classification

We performed offline single-trial classification analyses on the spatio-temporal domain in order to assess the extent to which AoA were detectable *in real-time*. Based on our results regarding spectral power modulations and on the literature on conflict monitoring [Coh14] we decided to focus the analyses on the θ frequency band [4-8Hz]. Epochs started 1000ms before the movement signal was given (“Go” signal) and ended 8000ms after the start of the signal. They were divided into 1s-long sliding windows, with a 1/16s step. For the classification phase, only a sub-part of the epochs –where EEG modulations were the most different between both *Synchronous* and *Manipulated* conditions– were considered, i.e., [-200 3000]ms (0ms being the “GO” signal). A common spatial pattern (CSP)⁵ [Bla+07] algorithm was used to determine the most discriminant spatial features between the conditions⁶. More precisely, three pairs of CSP filters were used. A regularised linear discriminant analysis (LDA) classifier [Bla+11] was then fed with these features. Both the CSP and LDA were trained on a training dataset and then tested on a testing dataset using a 5-fold cross-validation procedure (the data is split in 5 blocs of equal size, 4 of them are kept for training and the last one is used for testing). The results reported correspond to the peak classification accuracy. In other terms, the most discriminant time window was determined for each participant based on the training dataset alone. Then, the classification accuracy of this time window alone was used to compute the performance on the testing dataset. Other classification methods based on the spatial or temporal domains alone [Bla+11] were tested but resulted in similar classification accuracy. Table 3.1 aggregates results for all the participants. The classification accuracy ($M = 50.99$, $SD = 3.09$) could not be better than a random classifier for any participant (approximately 58%) [Mül+08]).

5. CSP is an algorithm for separating a signal into components in order to maximise the variance between two classes.

6. This is an important operation to do in EEG processing for robust analysis as the raw EEG scalp have poor spatial resolution due to volume conduction [Bla+07]. Spatial filtering has a neurophysiological meaning, as it helps to retrieve the original EEG signal (from the cortex and not the scalp) by integrating important information that got dispersed due to volume conduction. In addition, it reduces the dimensionality of the problem which is known to help classification.

Table 3.1 – Mean classification accuracy (CA) on a 5-fold cross-validation using a CSP (on the θ band) and a regularised LDA.

Subject	Mean CA (%)	Subject	Mean CA (%)
1	48.75	13	51.11
2	52.28	14	45.77
3	46.64	15	48.75
4	54.62	16	51.52
5	53.43	17	45.28
6	54.84	18	43.90
7	54.52	19	52.67
8	52.50	20	53.23
9	53.79	21	51.29
10	54.38	22	49.36
11	52.82	23	48.94
12	50.98	24	52.67

3.4 Discussion

Assessing AoA in real-time is of utmost interest to improve clinical diagnosis, rehabilitation procedures or to enhance VR applications, among other things. This requires deepening our understanding of AoA, and especially their neurophysiological correlates. Our objective was to assess the extent to which AoA, which were induced in VR via a distorted VR visual feedback, could be measured using surface EEG during natural hand movements. We show that neurophysiological correlates of AoA could be detected using surface EEG (which is an accessible and usable brain recording technique) during natural hand movements, i.e., lesser controlled tasks that approach ecological situations.

We obtained two main results. First, differences between both *Synchronous* and *Manipulated* conditions were also revealed by ERP analyses over the sensorimotor cortex. An N200 was elicited in the *Manipulated* condition only, supporting **H1**. While an N100 seems larger in the *Manipulated* condition, no significant difference was found. Likewise, a delayed P300 occurs in the *Manipulated* but there is no significant difference. Second, in contrast to *Synchronous*, *Manipulated* conditions are underlain by decreased spectral power in the θ frequency band over parieto-occipital in early stages of the trials (0-500ms), and in increased θ power in later time ranges over right parieto-temporal electrodes, contradicting **H2** in the early stages of the trials but supporting it in the later stages. Finally, based on these two results, a single-trial classification analysis was performed using several feature extraction methods, namely i) spatial and temporal information extracted

from the significant results of the ERP and spectral power analyses, and ii) the automatic selection of spatio-temporal features based on a machine learning approach (CSP analysis). None of these reached classification performances higher than chance level. In the following we discuss the findings in more detail.

The θ band is proposed as a frame of reference for monitoring and adjusting time sequential actions [CS15]. Thus, similarly to the conflict monitoring theory, we expected an increased θ activity (hypothesis **H2**) and an increased N200 (hypothesis **H1**) in the *Manipulated* condition which supposedly reflect a mismatch between the performed hand movement and the visual feedback displayed in VR [Coh14]. Indeed, we observed an increased N200 (validating **H1**) and θ power over the right parieto-temporo-central areas, yet only between 500 and 1000ms. In the 0-500ms time window, θ power was lower in the *Manipulated* than in the *Synchronous* condition over the parieto-occipital areas, being the opposite of what was expected with **H2**. This may be linked to other processes different than conflict monitoring theories. This unexpected result would be interesting to replicate with an independent sample in a future study, using an EEG set-up with more electrodes that will enable to perform source localisation analyses and better understand this result.

Thus, in the early expected time windows (0-500 ms), we observed mismatch differences in θ at parieto-occipital electrode sites, followed by maximum differences observed at the right parieto-temporal (500-1000 ms) electrode sites. This topographical configuration suggests a different neurophysiological mechanism than expected by conflict monitoring theories. From the perspective of the comparator model [DNV08], the topographical configurations of the left frontal and parietal would fit the expected role of the posterior parietal cortex (PPC) in the detection of visual-motor mismatches - although increased power would have been expected rather than decreased. Furthermore, our results regarding θ activity at later times (500-1000ms) could also be related to processes of motor behaviour optimisation, since this region is also involved in visual-spatial attention processes [Con06].

Finally, single trial classification analyses were not conclusive. This may be due to the fact that we could not precisely estimate the beginning of movement using this dataset - the hand movement tracking data had not been saved.

Altogether, these results suggest that EEG could be used to monitor AoA during natural movements, potentially using information extracted both from the spectral (θ power) and temporal (N200) domains.

3.4.1 Limitations

Despite our results, these analyses have some limitations.

First, the EEG analyses were made on the channels data (although pre-processed), which are measurements made on the scalp. Because of the conductivity of the scalp, the signal measured at an electrode is a linear combination of all measured electrodes activity. To solve that, there are many methods to analyse the EEG data at the level of cortical source dynamics, such as forward problems to determine the scalp projection patterns of the possible brain sources and inverse problems estimating the locations and orientations of cortical surfaces [Pio+15]. It is thus better to use source-resolved measures, that could effectively be computed with independent component analysis (ICA) [Del+12]. This could be made in a future study, using an EEG set-up with more electrodes that will enable to perform source localisation analyses.

Another limitation of this study is that the EEG epochs were time-locked to the stimulus onset (the “Go” signal) and not time-locked to the beginning of the movement. In this study, the hand tracking data were not saved, making impossible to detect when each movement started, and thus to time-lock the signal to the beginning of the movement. It would also be interesting to investigate the extent to which alterations of agency induced by the distorted feedback in VR correlate with modifications of the participants’ hand movements.

Finally, the classification could be improved by using other techniques that were not explored. In our case, we used a 1s-length sliding window with a 1/16s step, but all these windows were considered independently. It might have been better to use them all together, in order to accumulate evidence of classification over time, as the LDA can output probabilities. Solving both limitations mentioned in the paragraphs above could help improve the EEG signal quality and the resulting classification accuracy. The classification model used can also be questioned, as there are several other methods that have not been explored, such as those based on topological analysis [XDR21].

3.5 Conclusion

This chapter aimed at understanding the neurophysiological correlates of AoA, by analysing the EEG data from Jeunet et al.’s experiment [Jeu+18]. We showed that AoA elicited during natural hand movements using VR are characterised by specific modulations of both oscillatory activity and ERPs, that are detectable using surface EEG. This

paves the way for innovative methods to measure the SoA in out-of-the-lab settings and VR use case scenarios.

CONCLUSION

The purpose of this thesis entitled “**Evaluation and Manipulation of Virtual Embodiment**” was to improve the knowledge of the SoE evaluation and to be able to manipulate the SoE in VR. Two research questions were presented:

- Q1 **What is the interaction between the three components of the sense of embodiment?**
- Q2 **Are there neurophysiological markers of each component of the SoE that can be measured in real-time in a VR use case scenario?**

4.1 Contributions

In order to answer these questions, we presented in **chapter 2** an experiment on the manipulation of the SoE in VR, to answer **Q1**. The goal was to deepen the understanding of the SoE and the interactions between its components. This experiment is the first, to the best of our knowledge, to manipulate the three components of the SoE (namely, the SoA, SoBO and SoSL) in a single experiment. Analyses revealed that the experimental protocol we proposed does not allow independent manipulation of each SoE component. We could not replicate [MS14]’s results. This could be due to a difference in the experimental protocol and more specifically a different embodiment phase. In our case, visuomotor synchrony was used to elicit body ownership, whereas Maselli and Slater used visuotactile synchrony. Also, the duration of exposure is longer in their experiment. Also, the assessment of virtual embodiment is different as well because they used a 12-item questionnaire (compared to 3). Our results might also be explained by the fact that we used a non-anthropomorphic hand (which has, we believe, never been used before) and the impact it has on the SoA is unknown. Indeed, the hand could be perceived as inaccurate which could in turn influence the SoA. Nevertheless, results showed that the SoE components are tightly coupled.

This experiment also allowed to study the interaction between the SoA and the SoSL,

which, as reviewed in chapter 1, has not been done in the literature in VR. We found that changing the user’s point of view from 1PP to 3PP (starting from 20cm to the right) negatively impacts the SoA (as measured with our questionnaire), only in a condition where the SoA is not already manipulated. We argued that it could be explained by the fact that the SoA is already too low for the point of view change to have an effect. On the other way, the same interaction happened on the SoSL score for manipulating the SoA: the SoSL was lower when manipulating the SoA only in 1PP. This can be explained the same way as before. These results tend to show that the SoA and the SoSL are not independent unlike stated by David et al. [Dav+06], and are coherent with van den Bos’ and Jeannerod’s results [VJ02] that perspective taking (linked to the SoSL) influences the recognition of one’s action (linked to the SoA). Future studies should assess how both these components interact with each other to better predict their impact on experiments.

Finally, this experiment provides a basis for future experiments and allowed to confirm some results from the literature in a different but similar experiment (manipulating the SoA via biased visual feedback [Pad+16; Jeu+18]; manipulating the SoSL by changing the point of view from 1PP to 3PP [Len+07; Sla+10]; and manipulating the SoBO by changing the visual appearance of the avatar’s hand [LJ16; Arg+16; PE08]). This study should be extended with the use of standardised questionnaires [PG21] for a better evaluation of the SoE.

In **chapter 3**, we tried to answer part of **Q2** by focusing first on the SoA, the reason being we analysed EEG data from an already made VR experiment from Jeunet et al. [Jeu+18]. Our goal was to try to find EEG neurophysiological markers that characterise the SoA. We also attempted to create a classification model in order to see whether a real-time characterisation of the SoA was possible, as an alternative to questionnaires. We show that neurophysiological correlates of the SoA could be detected using surface EEG during natural hand movements. In the temporal domain, we observed differences of ERP over the sensorimotor cortex: an N200 was elicited only when the SoA was manipulated. In the spatial domain, our results show that the manipulation of the SoA implies a decreased spectral power in the θ frequency band (4-8Hz) over parieto-occipital electrodes in early stages of the trials (0-500ms), and in increased θ power in later time ranges over right parieto-temporal electrodes. Finally, we trained and tested a classification model using several feature extraction methods, namely i) spatial and temporal information extracted from the significant results of the ERP and spectral power analyses, and ii) the

automatic selection of spatio-temporal features based on a machine learning approach (CSP analysis). None of these could outperform a random classifier. The classification model used can be questioned, as there are several other methods that have not been explored, such as those based on topological analysis [XDR21]. We preferred to focus on other work instead of going further because it was not the core of this thesis.

These analysis allowed us to tackle a part of **Q2**, by finding relevant neurophysiological markers of the SoA using surface EEG. Following the user study presented in chapter 2, our objective was to perform the same study using EEG to find neurophysiological markers of the SoE, once the experimental protocol has been validated. We first analysed the data of Jeunet et al. [Jeu+18] since the experiment was already done. However, further experiments could not be made during this thesis, to try to answer the rest of **Q2**. Our results revealed that the experimental protocol we proposed does not allow independent manipulation of each SoE component, making it hard to perform the same experiment with EEG to find neurophysiological markers of the SoE. As such, if more time was dedicated to this thesis, it would be better to find with EEG neurophysiological markers of the SoBO and the SoSL in separate experiments before mixing everything together (more details below).

Finally, in addition to the review of literature, we suggested in chapter 1 criteria to compare the different evaluation methods of VEmb and some benefits and drawbacks of these. We defined these criteria based on what we believe is important for a VR use case. We hope these criteria will help VR researcher to select a measure depending on their use case. These are a first suggestion and this list might be refined in the future, with the consideration of well-defined VR scenarios (see below). Some of the key criteria for SoE measurement in VR are a real-time evaluation (in the order of milliseconds) and objective (i.e. independent from the user’s emotional/cognitive/motivational state), while being ecologically valid and reliable.

4.2 Perspectives

While this thesis provides insight to the manipulation and evaluation of the SoE in controlled experiments, these studies have some limitations and there are still many other paths to explore in order to have a reliable and objective measure of the SoE. In this section, we discuss directions of improvements for future research.

As presented in **chapter 1**, the definition of the SoE is evolving, with the attempts to create new standardised validated questionnaires [PG21; RL20], and deviating from the 3 sub-components of the SoE defined by Kilteni et al. [KGS12]. In addition to these 3 components, Peck and Gonzalez-Franco [PG21] also suggested motor control, tactile sensations, external appearance and response to an external stimuli, echoing De Vignemont’s categories of measures of embodiment being spatial measures (“is the space surrounding the embodied object processed as peripersonal space”), motor measures (does one feels that the embodied object “directly obeys one’s will” – similar to the SoA) and affective measures (does the embodied object is “protected from hazardous situations“ – already evaluated with galvanic skin response but not with questionnaires) [Vig11]. In their updated questionnaire, Peck and Gonzalez-Franco [PG21] did not include *Agency* as a category of evaluation of the SoE, but instead, the SoA is considered a transversal factor and SoA scores can be computed by merging questions of *Appearance*, *Ownership* and *Multi-Sensory* categories.

Likewise, Roth and Latoschik [RL20] suggested a new dimension of embodiment consisting in change in the perceived body schema. In chapter 1, we categorised the proprioceptive drift measure (“pointing where my hand or body is”) in the SoSL category, although correlations were found with the SoBO [BC98]. We categorised like this because it was referring to “where the body is”, although in the RHI experiment, the whole body scheme is updated, explaining this overlap of the SoBO and SoSL components. To summarise, we think that a redefinition of virtual embodiment would be beneficial to the VR community. Indeed, we have seen that the three components defined by Kilteni et al. [KGS12] are highly correlated and that makes the study of virtual embodiment more challenging. For instance, SoBO and SoSL are highly correlated, and there is sometimes overlap in their understanding. In other words, perhaps we are looking at the same object from two different angles, and we could, for example, only be interested in the perception of the body schema, as explored by Roth and Latoschik [RL20].

Nevertheless, having one standardised questionnaire for all experiments is not an easy task when trying to measure such a complex phenomenon. Although Peck and Gonzalez-Franco [PG21] suggest ways to adapt their questionnaire to different experimental designs, it may introduce some variability in the experiments. Another idea to standardise future VR embodiment experiments could be to design small but tailored questionnaires that could be put together in a modular way, as already done for assessing user experience in VR [Wie+18]. Instead of adapting questionnaire items to particular experiments, the VR

community researchers would have to use the question as-is, but could remove non-relevant questions. For instance, removing questions related to foot tracking when it is not taken into account in the experiment. This raises an important question: is it relevant to the variety of use cases in VR and the individuality of the experience a person can have with VR? Indeed, as noted in the introduction, the SoE is a subjective feeling, also defined in philosophy as a *qualia* (the subjective content of the experience of a mental state). It may be more appropriate to have multiple various VR scenarios instead (see further below). We believe however the community would greatly profit of better comparison of VR embodiment experiments, as emphasised by Peck and Gonzalez-Franco [PG21].

We have seen the alternatives to questionnaires, namely behavioural measures and physio- and neurophysiological measures. Correlations have been found with the SoA, SoBO or the SoSL evaluated via questionnaires for behavioural measures [Gon+10; Kil+12; Fri+18], physiological measures [Sla+10; PS13] and neurophysiological measures [Ehr+07; Gon+14; Jeu+18]. Nevertheless, these measures are not always correlated between them despite showing similar effects. For instance there is no correlation between explicit (rating scales and surveys [DK14]) and implicit (intentional binding [HCK02] and sensory attenuation [BWF98]) measures of the SoA [DK14]. The literature shows that these measures rely on “data sources that overlap, but not completely” as stated by Ma et al. [Ma+21]. In their VR experiment, Ma et al. used two different SoBO measures (explicit SoBO ratings measured via questionnaires adapted from [BC98] and [KE14], and proprioceptive drift as an implicit measure of the SoBO) and found no correlation between these two measures. Moreover, they were differently affected by the independent variables in their experiment (the participants controlled either a virtual hand or a virtual triangle to represent their hand). As defended in this thesis, a possible viable solution for the future is to measure brain signals with an EEG headset, although not the perfect solution either. First, the interpretation and the analysis of EEG requires a certain expertise. Then, there are a lot of improvements needed in order to effectively measure the SoE in VR. EEG signal-to-noise ratio is still poor, it is greatly impacted by (mainly head) movements making the measure less accurate. It also forces the user to wear another headset, which can be cumbersome. Improvement in EEG processing, with better knowledge of the SoE will help to measure the SoE using EEG. Better artefact rejection and correction will improve the signal-to-noise ratio and allow a better single trial classification. In addition to classical methods (such as linear discriminant analysis) neural networks have also been used to classify EEG signals [SE05] and seems promising for the future.

We have presented in chapter 3 an EEG analysis of Jeunet’s et al. experiment [Jeu+18], that answers part of **Q2**, by focusing on the study of the SoA. Similar studies should be made regarding the SoBO and the SoSL. Results from the literature found an increase of the EEG θ power over frontal and parietal areas [BCC11; EB13] for SoBO manipulations and a modulation of the EEG α power (8-12Hz) over the sensorimotor cortex when manipulating the SoSL [LHB11]. Before studying the SoBO and the SoSL neurophysiological markers in a similar way of the experiment in chapter 3, we should validate with an experiment that they can be selectively manipulated as in [MS14]. A further understanding of the processes involved in both the SoBO and SoSL would help designing such experiments in the future. An important part of **Q2** relates to a “**VR use case scenario**”. While participants performed natural hand movements, it is not clearly yet a VR use case scenario. Indeed, participants could not move their head anywhere they wanted as the Oculus Rift was supported by an articulated arm, to avoid any pressure on the EEG headset. The experimental design we propose in chapter 2 goes a step further allowing head movement¹ while preserving natural hand movements. Further experiments should be made in more realistic VR scenarios like in Fribourg’s et al. work [Fri+18] (hit a punching bag, hit a soccer ball, follow fitness movement, with no interaction with the environment or a walking task with obstacles to avoid). Indeed, apart from controlled experiments, VR is also intended to be used in real life uncontrolled scenarios, and it is important to study virtual embodiment in realistic scenarios. The impact of different factors could change depending on the type of task, and it is important to better understand whether this is the case or not. We think the several realistic and varied scenarios proposed by Fribourg’s et al. [Fri+18] are a good basis. One could go further by proposing a standardisation of scenarios in VR to have a good representation of the virtual embodiment and promote comparability between experiences.

In the context of realistic VR scenarios, it is questionable whether the study of the SoSL is relevant. However, it is still important to take into account in the study of SoE (in general and its application in VR) to better understand this phenomenon. In addition to VR scenarios, a methodological guide for an optimal virtual embodiment would have been interesting to propose during this thesis. Although this has not been considered, we think there are still too many areas to explore on virtual embodiment to have rules and establish a guide. This remains a possibility for future study, nonetheless.

1. However, in our experiment, no EEG headset was used, so we did not have the constraint of the pressure of the VR headset on the EEG headset.

To summarise, there are still many paths to explore following this thesis (a visual summary is presented in Figure 4.1). Our first research question **Q1** was about the interaction of the SoE components. While we explored different factors impacting each component, further experiments are necessary in order to better understand the processes involved in the SoA, SoBO and SoSL. As mentioned, we are not sure of the impact on the SoA of the *Stickfingers* hand we used, and we could not replicate the work of Maselli and Slater [MS14] where they selectively alter the SoBO and the SoSL. The use of standardised questionnaires would also allow better comparability between experiments. The experiment presented in chapter 2 is the first, to the best of our knowledge, to manipulate the three components of the SoE in a single experiment and more experiments should be made in this way too. Nevertheless, it can also be interesting to first better understand the different processes involved in the SoE and its components with smaller controlled experiments before grouping everything together. Our second research question **Q2** was about neurophysiological markers of the components of the SoE, measured in **real-time** and in a **VR use case scenario**. As explained before (and displayed in Figure 4.1), experiments should use VR case scenario while measuring the SoA with EEG, and the measurement of the other components (namely the SoBO and the SoSL) with EEG in VR should be explored.

As an ending note, previous research has shown that the SoA could be shared with others in the context of joint actions [Sil+21; Loe22]. There would exist a collective SoA in such contexts. In this way, the SoA of users over their avatar could not be only perceived as direct control but the avatar could be considered as a partner and feel SoA for it without necessarily being embodied in the avatar. Users could also experience an extended SoA towards their avatar [LPG23; WHS11b]. These components of the SoA have not been considered in this thesis, but could totally be important factors of the SoA. In this way, this should be taken into account in the future in the overall definition of virtual embodiment.

Galileo Galilei said “*Measure what is measurable, and make measurable what is not so*”. This thesis tries to go forward in that direction. We hope this thesis will help the VR community with a better understanding of the SoE and its evaluation in VR, provide experimental basis for future studies and new insight to the interaction of the SoA, the SoBO and the SoSL.

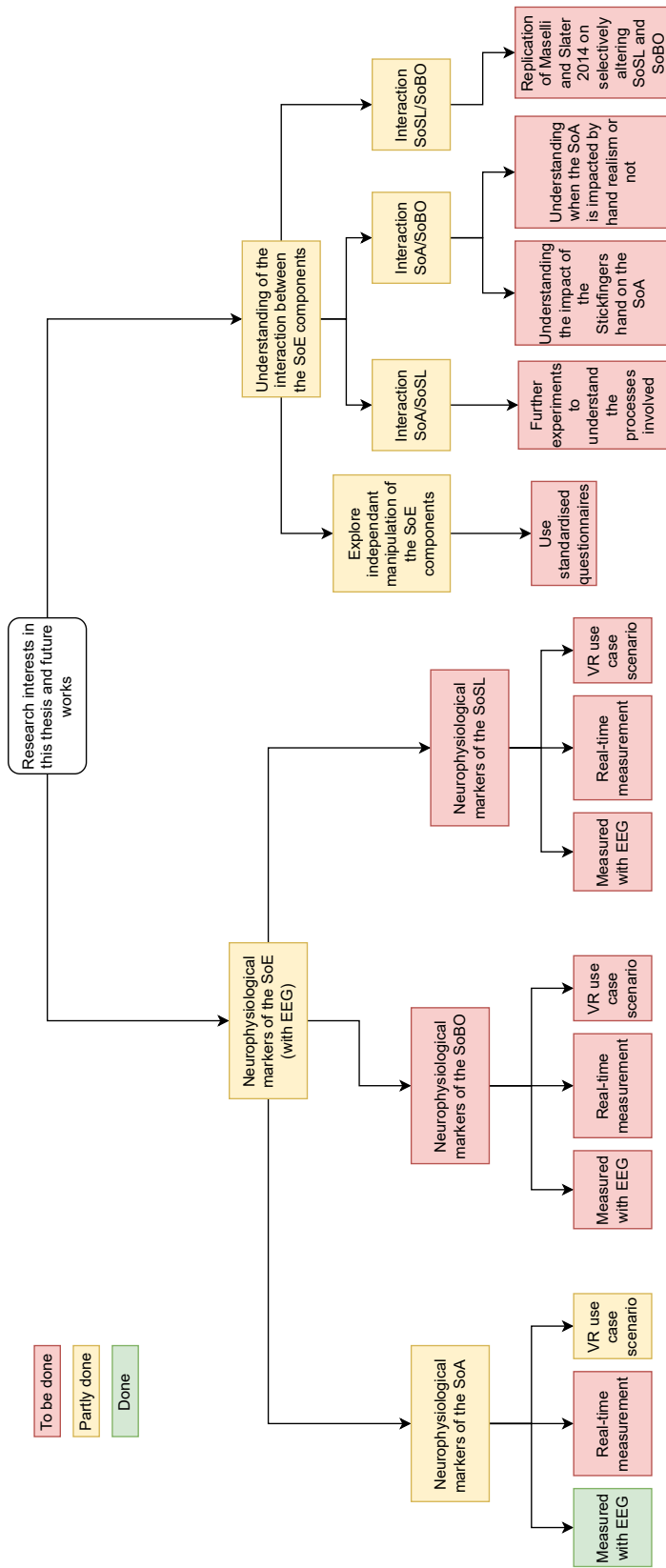


Figure 4.1 – Summary of the contributions and open questions remaining in this thesis.

ANALYSIS DATA OF CHAPTER 2

This appendix represents the full analysis data from the experiment presented in chapter 2.

A.1 SoA score s_soa

A.1.1 Descriptive Statistics

<i>SoA-manipulation</i>	<i>SoSL-manipulation</i>	<i>SoBO-manipulation</i>	mean	std
Manipulated	1PP	Anthropomorphic-hand	3.170	1.227
		Stick-fingers	3.245	0.993
	3PP-EP	Anthropomorphic-hand	3.259	1.231
		Stick-fingers	2.972	1.011
	3PP-PP	Anthropomorphic-hand	3.298	1.232
		Stick-fingers	3.230	1.249
Synchronous	1PP	Anthropomorphic-hand	6.078	0.796
		Stick-fingers	5.089	1.254
	3PP-EP	Anthropomorphic-hand	5.461	1.078
		Stick-fingers	4.677	1.080
	3PP-PP	Anthropomorphic-hand	5.574	0.859
		Stick-fingers	4.922	1.052

Table A.1 – Descriptive statistics of the SoA score ($N = 47$).

A.1.2 ANOVA table (Type 3 tests)

Effect	df	MSE	F	η_p^2	p -value
<i>SoA-manipulation</i>	1, 46	1.73	360.48 ***	0.887	<0.001
<i>SoBO-manipulation</i>	1, 46	0.68	42.27 ***	0.479	<0.001
<i>SoSL-manipulation</i>	1.75, 80.35	1.00	4.96 *	0.097	0.012
<i>SoA-manipulation:SoBO-manipulation</i>	1, 46	0.66	27.45 ***	0.374	<0.001
<i>SoA-manipulation:SoSL-manipulation</i>	2, 92	0.55	4.73 *	0.093	0.011
<i>SoBO-manipulation:SoSL-manipulation</i>	1.98, 90.86	0.48	0.77	0.016	0.465
<i>SoA-manipulation:SoBO-manipulation:SoSL-manipulation</i>	2, 92	0.51	2.14	0.045	0.123

Table A.2 – ANOVA Table where the dependent variable is the SoA score (s_soa).

A.2 SoSL score s_sosl

A.2.1 Descriptive Statistics

SoA-manipulation	SoSL-manipulation	SoBO-manipulation	mean	std
Manipulated	1PP	Anthropomorphic-hand	5.780	1.257
		Stick-fingers	5.255	1.394
	3PP-EP	Anthropomorphic-hand	2.025	1.196
		Stick-fingers	1.901	1.173
	3PP-PP	Anthropomorphic-hand	2.830	1.253
		Stick-fingers	2.819	1.445
Synchronous	1PP	Anthropomorphic-hand	6.362	0.691
		Stick-fingers	5.752	1.238
	3PP-EP	Anthropomorphic-hand	2.113	1.368
		Stick-fingers	2.106	1.383
	3PP-PP	Anthropomorphic-hand	3.270	1.490
		Stick-fingers	3.028	1.372

Table A.3 – Descriptive statistics of the SoSL score ($N = 47$).

A.2.2 ANOVA table (Type 3 tests)

Effect	df	MSE	F	η_p^2	p -value
<i>SoA-manipulation</i>	1, 46	0.76	21.04 ***	0.314	<0.001
<i>SoBO-manipulation</i>	1, 46	0.63	14.30 ***	0.237	<0.001
<i>SoSL-manipulation</i>	1.45, 66.48	4.59	215.74 ***	0.824	<0.001
<i>SoA-manipulation:SoBO-manipulation</i>	1, 46	0.35	0.44	0.009	0.510
<i>SoA-manipulation:SoSL-manipulation</i>	1.72, 79.25	0.40	5.29 **	0.103	0.010
<i>SoBO-manipulation:SoSL-manipulation</i>	1.82, 83.92	0.44	8.73 ***	0.159	<0.001
<i>SoA-manipulation:SoBO-manipulation:SoSL-manipulation</i>	1.96, 90.38	0.36	1.01	0.021	0.368

Table A.4 – ANOVA Table where the dependent variable is the SoSL score (s_sosl).

A.3 SoBO score s_sobo

A.3.1 Descriptive Statistics

SoA-manipulation	SoSL-manipulation	SoBO-manipulation	mean	std
Manipulated	1PP	Anthropomorphic-hand	4.007	1.459
		Stick-fingers	2.908	1.407
	3PP-EP	Anthropomorphic-hand	3.270	1.447
		Stick-fingers	2.131	1.073
	3PP-PP	Anthropomorphic-hand	3.440	1.269
		Stick-fingers	2.514	1.318
Synchronous	1PP	Anthropomorphic-hand	5.624	1.046
		Stick-fingers	3.652	1.684
	3PP-EP	Anthropomorphic-hand	4.089	1.501
		Stick-fingers	2.773	1.326
	3PP-PP	Anthropomorphic-hand	4.610	1.416
		Stick-fingers	3.145	1.457

Table A.5 – Descriptive statistics of the SoBO score ($N = 47$).

A.3.2 ANOVA table (Type 3 tests)

Effect	df	MSE	F	η_p^2	p -value
<i>SoA-manipulation</i>	1, 46	1.17	105.56 ***	0.696	<0.001
<i>SoBO-manipulation</i>	1, 46	2.54	96.69 ***	0.678	<0.001
<i>SoSL-manipulation</i>	1.54, 70.84	1.07	56.12 ***	0.550	<0.001
<i>SoA-manipulation:SoBO-manipulation</i>	1, 46	0.41	24.29 ***	0.346	<0.001
<i>SoA-manipulation:SoSL-manipulation</i>	2, 92	0.37	6.56 **	0.125	0.002
<i>SoBO-manipulation:SoSL-manipulation</i>	1.96, 90.14	0.58	2.94	0.060	0.059
<i>SoA-manipulation:SoBO-manipulation:SoSL-manipulation</i>	1.98, 91.15	0.44	3.24 *	0.066	0.044

Table A.6 – ANOVA Table where the dependent variable is the SoBO score (s_sobo).

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RESUMÉ LONG EN FRANÇAIS

Cette thèse intitulée “**Évaluation et manipulation de l’incarnation virtuelle**” étudie le sentiment d’avoir un corps en réalité virtuelle (RV). Pour mieux comprendre ce sentiment, l’accent sera mis sur l’évaluation et la manipulation de celui-ci dans le cadre d’expériences. De Vignemont disait que notre corps doit être l’objet que l’on connaît le mieux [Vig11]. Nous l’utilisons tous les jours, nous recevons en permanence des informations sensorielles. Pourtant, que signifie phénoménologiquement le fait d’avoir un corps ? Chez les personnes saines, ce sentiment n’est généralement pas remis en question dans la vie de tous les jours. En psychologie cognitive, on parle du sentiment d’incarnation, telle que défini par Blanke et al. [BM09] :

Sentiment d’incarnation

Le sentiment d’incarnation est l’expérience subjective d’utiliser et d’avoir un corps [BM09].

Contexte

Une meilleure compréhension de l’incarnation, en plus d’en apprendre davantage sur la conscience de soi et du corps, permettrait un certain nombre d’applications. En effet, l’évaluation et la manipulation de l’incarnation pourraient aider les gens à se sentir incarnés :

- dans la vie réelle (pour les personnes souffrant de troubles tels que la somato-paraphrénie [VR09], la dépersonnalisation [Sie+05] ou le trouble de l’identité de l’intégrité corporelle [FF12]), afin de mieux étudier les troubles et donc de mieux les traiter. Par exemple, dans le cas de la dépersonnalisation, les personnes ont un sentiment de soi amoindri et une incarnation altéré vis-à-vis de leur propre corps [FS09] ;
- dans un environnement simulé (simulant la réalité) pour une meilleure immersion et un plus grand réalisme.



FIGURE A.1 – (a) Exemple de CAVE nommé Immersia situé à Rennes, France. (b) Exemple d’un visiocasque/HMD. L’utilisateur est un astronaute s’entraînant en RV à éteindre un feu dans un habitat lunaire. De ESA, CC BY-SA IGO 3.0.

L’incarnation n’est pas facile à manipuler dans la vie de tous les jours : nous ne pouvons pas changer instantanément notre point de vue et nous voir à la troisième personne, ni changer notre corps ou les conséquences de nos actions. Cependant, ces choses peuvent être facilement réalisées grâce à la technologie, avec l’aide de RV.

La réalité virtuelle (RV) a plusieurs définitions. Une première, technique, de Arnaldi et al. [AFT03], définit la RV comme une réalité créée par la technologie, “exploitant l’informatique et des interfaces comportementales” pour simuler des entités 3D dans un monde virtuel qui interagissent en temps réel.

La RV immerge les utilisateurs dans un monde virtuel par différents moyens techniques (voir figure A.1). Dans le cadre de cette thèse, nous nous concentrons sur la RV immersive utilisant des visiocasques (ou HMD de l’anglais).

En RV, il est possible d’être représenté par un corps virtuel, aussi appelé un avatar. C’est ce qu’on appelle l’incarnation virtuelle (IV), définie par Spanglang et al :

Incarnation Virtuelle

L’incarnation virtuelle (IV) est le processus physique qui utilise la RV pour remplacer le corps d’une personne par un corps virtuel. [Spa+14]

Un avatar peut prendre toute forme : une représentation haute qualité et réaliste de l'utilisateur ou même une représentation abstraite d'un corps (voir figure A.2). Dans le contexte de la RV, il a été démontré que l'utilisation d'un avatar apporte des avantages, comme une amélioration des performances des utilisateurs dans les tâches cognitives [PS19] ou la réduction de la charge cognitive [Ste+16].

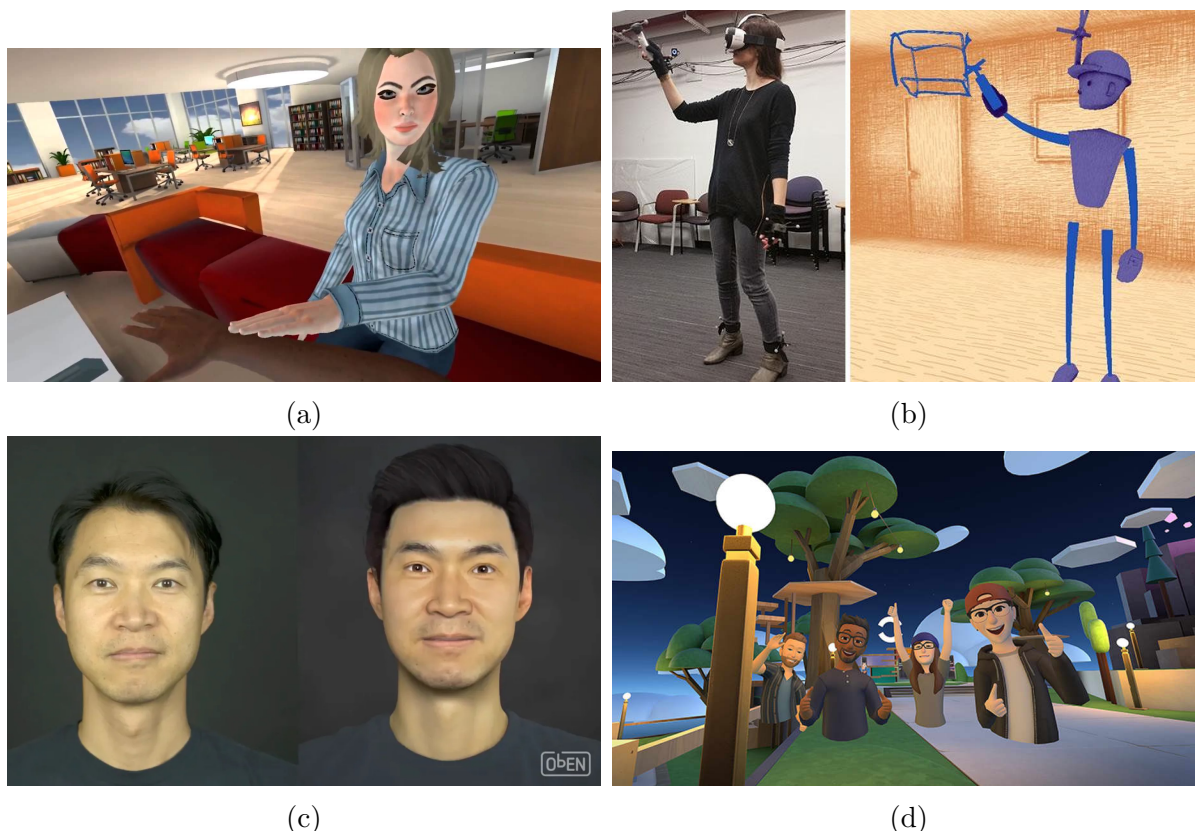


FIGURE A.2 – Différents types d'avatars utilisés en RV. (a) Avatar du projet beingavatar ; (b) Avatar abstrait. (Ken Perlin's Holojam virtual reality system, photographie de Sebastian Herscher, Holojam Artwork de David Lobser) ; (c) Le co-fondateur d'ObEN Adam Zheng et son avatar photoréaliste ; (d) Avatars cartoon (corps incomplets) dans Horizon World de Facebook (picture from Meta).

Évaluation de l'incarnation virtuelle

L'étude de l'IV a permis de montrer qu'il était possible de modifier la perception du corps d'un utilisateur [Kil+12 ; Pec+13 ; Lom+19], voire même que des changements plus profonds de comportement étaient possibles. L'utilisateur "se voit" dans la RV avec un corps, qui va impacter sa perception et son comportement [Rei+20 ; YPD15].

L'évaluation de l'IV est cependant complexe car il s'agit d'un sentiment subjectif, également défini en philosophie comme une *qualia* (le contenu subjectif de l'expérience d'un état mental). Actuellement, le consensus pour l'évaluation de l'IV est d'utiliser des questionnaires standardisés [KGS12; GP18]. L'avantage de ces questionnaires est leur facilité d'utilisation. Cependant, ils présentent également des inconvénients : les questionnaires ne peuvent être remplis que rétrospectivement et non en continu, ce qui oblige l'utilisateur à effectuer une tâche supplémentaire. En outre, l'interprétation des questions peut varier d'un sujet à l'autre et à l'intérieur d'un même sujet [Sla04].

D'autres mesures dites quantitatives ont également vu le jour, utilisant des signaux physiologiques, tels que l'activité électrodermale (ou GSR en anglais) — l'activité électrique biologique enregistrée à la surface de la peau — ou des signaux neurophysiologiques tels que l'électroencéphalographie (EEG) — la mesure de l'activité électrique du cerveau à l'aide d'électrodes. Les avantages de ces mesures sont qu'elles n'impliquent pas activement l'utilisateur et qu'elles peuvent être effectuées tout au long d'une expérience. Toutefois, ces mesures présentent également des inconvénients. Qu'il s'agisse de mesures physiologiques ou neurophysiologiques, elles sont sensibles au bruit et nécessitent souvent une valeur de référence. Le principal inconvénient des mesures physiologiques est leur manque de spécificité. En effet, les modulations de la fréquence cardiaque ou du GSR peuvent être dues à des altérations de l'IV, mais aussi à d'autres facteurs internes ou externes tels que le rythme circadien ou les modulations de la température ambiante, respectivement. Enfin, l'utilisation simultanée d'un casque EEG et d'un casque de RV est également difficile. C'est pourquoi les questionnaires restent prédominants aujourd'hui [TM19; GP18; Jeu+18; AFL19].

Champ d'application et questions de recherche

L'IV est aussi étudiée en neurosciences, où l'on cherche à trouver et comprendre les corrélats neuronaux liés au fait d'avoir et de contrôler un corps. Elle est également étudiée en philosophie et en science cognitive, où l'on questionne le soi et la conscience de soi. Dans le cadre de cette thèse, nous nous concentrons sur les avatars dans le contexte de la RV immersive utilisant des HMD. L'utilisateur incarne un avatar qui lui permet d'interagir avec l'environnement virtuel dans lequel il se trouve et peut avoir l'impression que l'avatar est son propre corps [KGS12]. L'étude de l'incarnation est également importante pour mieux comprendre les processus cognitifs et inversement. Ainsi, nous utiliserons une approche interdisciplinaire en utilisant des connaissances en RV et en neurosciences.

L'IV est communément caractérisée par 3 composantes, définies par Kilteni et al. [KGS12] : le SoSL (localisation de soi) ; le SoA (agentivité) ; et le SoBO (possession de corps). Le SoA est le sentiment d'être la cause de nos actions. Le SoBO est l'auto-attribution d'un corps. Enfin, le SoSL est "l'expérience spatiale d'être à l'intérieur d'un corps" [KGS12]. Cependant, les relations et les interactions entre ces trois composantes ne sont toujours pas claires, en particulier dans le contexte de la RV [KGS12]. Pouvoir manipuler et mesurer l'IV (et chacune de ses composantes) de manière fiable permettrait de mener des études plus fondamentales qui pourraient aboutir à une meilleure connaissance du fonctionnement du cerveau, notamment dans le cadre de certaines pathologies telles que les troubles dissociatifs où la relation au corps est altérée. Une façon de mesurer l'IV est d'évaluer chacune de ses composantes et pour cela il faut pouvoir manipuler chaque composante dans des études expérimentales.

Notre travail se concentre enfin sur deux questions de recherche :

Q1 Quelle est l'interaction entre les trois composantes du sens de l'incarnation ?

Nous nous intéresserons plus particulièrement à la manipulation indépendante de chaque composante dans un cadre expérimental. En effet, la possibilité d'isoler ces composantes faciliterait les protocoles et la conception d'expériences.

Q2 Y a-t-il des marqueurs neurophysiologiques de chaque composante de l'IV pouvant être mesurés en temps réel dans un scénario d'utilisation en RV ? Une fois que des protocoles expérimentales sont validés et que les marqueurs neurophysiologiques peuvent être mesurés, nous avons toujours besoin d'une mesure en temps réel pour l'appliquer en RV.

Dans les prochaines sections, nous présentons nos différentes contributions pour mieux comprendre l'interaction entre les composantes, et des marqueurs neurophysiologiques de l'incarnation virtuelle.

Étude de l'interaction entre les composantes du sentiment d'incarnation

Dans le chapitre 2 de cette thèse, nous présentons une expérience utilisateurs tentant de répondre à **Q1**. Nous explorons les relations entre les sous-composants de l'IV pour approfondir la connaissance sur l'IV et des interactions entre ses sous-composantes. Notre question de recherche est la suivante : "Chaque sous-composante de l'IV peut-elle être ma-

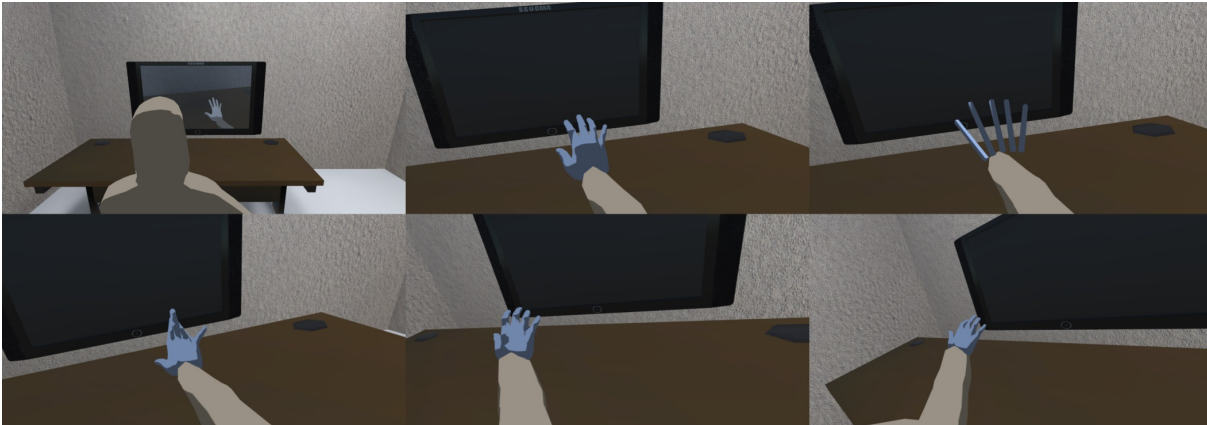


FIGURE A.3 – Cette expérience a évalué le sentiment d’incarnation pendant des mouvements de la main droite avec différents niveaux d’agentivité, différents niveaux de réalisme de la main virtuelle et différents niveaux de localisation de soi. (En haut à gauche) Vue d’ensemble de l’environnement virtuel utilisé dans l’expérience. L’avatar du participant est assis sur une chaise, devant une table où se trouve un écran affichant des vidéos et des signaux. (Au milieu en haut et en haut à droite) Perspective à la première personne (1PP) de la main anthropomorphe de dessin animé (*Main-anthropomorphe*) et de la main en forme de bâton (*Main-batons*). En bas (de gauche à droite) : 2^e et 4^e doigts inversés (*Manipulé*) en 1PP, perspective à la troisième personne dans l’espace péripersonnel (3PP – PP), perspective à la troisième personne dans l’espace extrapersonnel (3PP – EP).

nipulée de manière indépendante?”. Pour répondre à cette question, nous avons conçu une expérience intra-sujet dans laquelle 47 participants droitiers devaient effectuer des mouvements de leur main droite dans différentes conditions expérimentales ayant un impact sur les sous-composantes de l’incarnation : le SoA était modifié en impactant le contrôle de l’avatar avec un retour visuel biaisé, le SoBO était modifié en modifiant le réalisme de la main droite virtuelle (main de dessin animé anthropomorphe ou des “doigts” bâton non anthropomorphes) et le SoSL était contrôlé par le point de vue de l’utilisateur (à la première ou à la troisième personne). Après chaque essai, les participants ont évalué leur niveau de SoA, de SoBO et de SoSL sur une échelle de Likert à 7 niveaux. L’analyse des résultats a révélé que les trois composantes ne pouvaient pas être modifiées de manière sélective dans cette expérience. Néanmoins, ces résultats préliminaires ouvrent la voie à d’autres études.

Cette expérience a également permis d’étudier l’interaction entre le SoA et le SoSL, ce qui, comme indiqué dans le chapitre 1, n’a pas été fait dans la littérature en RV. Nous avons constaté que changer le point de vue de l’utilisateur de 1PP à 3PP (en commençant

à 20 cm à droite) a un impact négatif sur le SoA (mesuré à l'aide de notre questionnaire), uniquement lorsque le SoA n'est pas déjà manipulé. Nous pensons que cela peut s'expliquer par le fait que le SoA est déjà trop faible pour que le changement de point de vue ait un effet. En revanche, la même interaction s'est produite sur le score de SoSL lors de la manipulation du SoA : le score de SoSL était plus faible lorsque l'on manipulait SoA, mais uniquement en 1PP. Cela s'explique de la même manière que précédemment. Ces résultats tendent à montrer que le SoA et le SoSL ne sont pas indépendants, contrairement à ce qu'affirment David et al. [Dav+06], et sont cohérents avec les résultats de van den Bos et Jeannerod [VJ02] selon lesquels la perspective (liée au SoSL) influence la reconnaissance de l'action (liée au SoA). Les études futures devraient évaluer comment ces deux composantes interagissent entre elles afin de mieux prédire leur impact sur les expériences.

Marqueurs neurophysiologique du sentiment d'agentivité (SoA)

Dans le chapitre 3 de cette thèse, nous nous concentrons sur **Q2**. Pour répondre à cette question, il est plus pertinent d'étudier l'IV séparément, une composante à la fois. Suite à l'étude utilisateur présentée dans le chapitre 2, notre objectif était de réaliser la même étude en utilisant de l'EEG pour trouver des marqueurs neurophysiologiques de l'IV, une fois le protocole expérimental validé. Cependant, Jeunet et al. [Jeu+18] ont réalisé une expérience en RV qui consistait à manipuler le SoA des participants, au cours de laquelle ils ont mesuré l'activité EEG des participants. Ces signaux EEG n'ayant pas été entièrement analysés, nous avons décidé de procéder à une analyse plus approfondie de ces données. Dans ce chapitre, nous nous attachons donc à répondre en partie à **Q2**, en nous concentrant sur SoA.

Le SoA est un concept de la plus haute importance, tant d'un point de vue individuel que social, car il régit le sens de la responsabilité que nous avons à l'égard de nos propres actions. Pourtant, il peut être altéré, par exemple en raison de conditions cliniques (p. ex. troubles dissociatifs) ou lorsqu'une technologie ne répond pas comme prévu à nos commandes. Dans ce chapitre, notre objectif était d'évaluer dans quelle mesure les altérations du SoA pouvaient être mesurées lors de différents mouvements naturels de la main à l'aide de l'EEG de surface, qui est compatible avec les mesures hors laboratoire (par exemple, pour l'évaluation clinique ou l'évaluation d'une technologie). Nous avons analysé les données EEG (N=24) recueillies à l'aide d'un protocole de RV validé qui permet d'induire

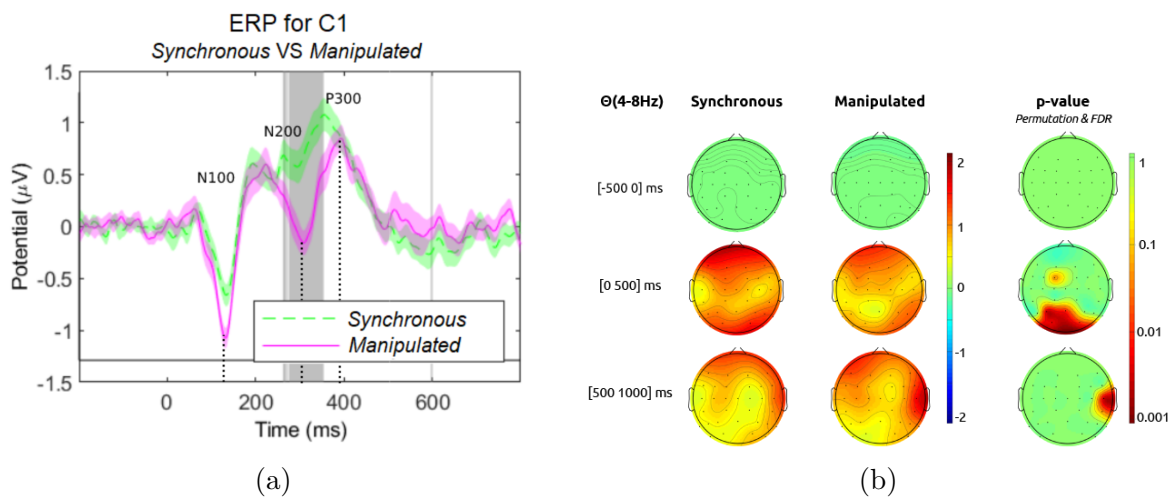


FIGURE A.4 – Dans cette contribution, nous analysons les signaux EEG mesurés lors de l’expérience de Jeunet et al. [Jeu+18] pour trouver des marqueurs neurophysiologiques du SoA. (a) Potentiel évoqué en C1 (Synchrone vs Manipulé). On observe une N200 dans la condition Manipulé pouvant refléter un processus de monitoring d’action ; (b) Perturbations spectrales sur la bande θ (4-8Hz) lors de la référence (500ms avant l’essai), du début de la répétition (0-500ms) et lors du traitement du retour visuel (500-1000ms). On observe une diminution de la puissance θ dans les zones sensorimotrices et pariéto-occipitales au début des essais (0-500ms) suivie d’une augmentation dans les zones temporo-pariétales droites (500-1000ms).

une perception de l'action en déformant le retour visuel fourni aux participants pendant les mouvements naturels de la main droite. Nous avons été en mesure d'identifier différentes modulations EEG qui pourraient refléter les altérations de SoA. Tout d'abord, une N200 est apparue uniquement dans la condition où le SoA est manipulé). Deuxièmement, contrairement à la condition synchrone (où le mouvement en RV de l'utilisateur n'est pas manipulé), la condition manipulée semble caractérisée par une diminution de la puissance θ dans les zones sensorimotrices et pariéto-occipitales au début des essais (0-500ms) suivie d'une augmentation dans les zones temporo-pariétales droites (500-1000ms). Bien que ce changement soit inattendu, ces résultats sont cohérents avec la théorie de la gestion de conflits dans la dernière phase des essais (500-1000ms). Toutefois, ces résultats devraient être confirmés dans une nouvelle expérience cherchant spécifiquement à prouver ces résultats.

Après avoir trouvé sur de grandes moyennes ces marqueurs temporels et spatiaux caractérisant le SoA, nous avons également essayé de détecter ces marqueurs à l'échelle d'un individu, pour envisager la détection en temps réel de ces marqueurs, en faisant de la classification essai unique. Nous avons formé et testé un modèle de classification utilisant plusieurs méthodes d'extraction de caractéristiques, à savoir i) des informations spatiales et temporelles extraites des résultats significatifs des analyses ERP et de puissance spectrale, et ii) la sélection automatique de caractéristiques spatio-temporelles basée sur une approche d'apprentissage automatique (analyse CSP). Aucune de ces méthodes n'a pu cependant surpasser un classificateur aléatoire.

Critères de comparaison des méthodes d'évaluation de l'incarnation virtuelle

Enfin, en plus de la revue de littérature du chapitre 1, nous avons proposé des critères pour comparer les différentes méthodes d'évaluation de l'IV et certains de leurs avantages et inconvénients. Nous avons défini ces critères sur la base de ce que nous estimons être important pour un cas d'utilisation en RV. Nous avons identifié 3 types de critères d'évaluations qui nous semblent importants en RV pour l'évaluation de l'IV : **situation écologique** de l'évaluation, **subjectivité de la mesure** et le **traitement des données**. Enfin, nous avons séparé les critères en deux catégories selon qu'ils concernent les mesures ou les protocoles expérimentaux. En effet, certains outils de mesure imposent des contraintes à l'utilisateur, et certains protocoles expérimentaux peuvent être utilisés avec

différents outils de mesure.

Critères liés aux mesures :

- **Dépendante d'un protocole** : La mesure nécessite l'utilisation d'un protocole expérimental particulier.
- **Écologique** : La mesure oblige, restreint ou interdit à l'utilisateur d'effectuer certaines actions.
- **Auto-évaluation** : La mesure est une évaluation subjective de l'utilisateur (donnée oralement ou par écrit).
- **Seconde tâche** : La mesure est une tâche en soi (l'accès à la mesure requiert une tâche particulière de la part du participant).
- **Mesure en temps réel** : L'acquisition des données se fait en temps réel (de l'ordre de la milliseconde).
- **Traitement en temps réel** : Le traitement (et l'interprétation) des données se fait en temps réel.
- **Exigence cognitive** : La mesure fait appel aux fonctions cognitives de l'utilisateur (attention, mémoire, inhibition).
- **Besoin d'une valeur de référence (par exemple au repos)** : La mesure présente des variations inter-personnelles et nécessite une valeur de référence pour être interprétée.
- **Sensible aux artefacts** : L'acquisition de la mesure contient des artefacts.

Critères liés au protocole :

- **Écologique** : La mesure oblige ou interdit à l'utilisateur d'effectuer certaines actions.
- **Seconde tâche** : Une tâche supplémentaire du participant est nécessaire pour accéder au processus mesuré.
- **Exigence cognitive** : Le protocole fait appel aux fonctions cognitives de l'utilisateur (attention, mémoire, inhibition).
- **Émotionnellement désagréable** : Le protocole provoque des émotions désagréables chez l'utilisateur (ennui, peur, colère, malaise, inconfort, etc.).
- **Besoin de personnes supplémentaires** : Le protocole nécessite l'intervention d'autres personnes (interviewer, observateur, etc.).

Nous espérons que ces critères aideront les chercheurs en RV à sélectionner une mesure en fonction de leur cas d'utilisation. Il s'agit d'une première suggestion et cette liste pourrait être affinée à l'avenir, en tenant compte de scénarios de RV bien définis. Cer-

tains des critères clés de la mesure de l'IV en RV sont une évaluation en temps réel (de l'ordre de la milliseconde) et objective (c'est-à-dire indépendante de l'état émotionnel/cognitif/motivationnel de l'utilisateur), tout en étant écologiquement valide et fiable.

Conclusion

L'objectif de cette thèse était d'améliorer la connaissance de l'évaluation de l'IV et de pouvoir manipuler l'IV en RV. Nous avons défini 2 questions de recherche et proposé deux contributions pour mieux comprendre l'interaction entre les composantes de l'incarnation virtuelle et la mesure de l'incarnation virtuelle en temps réel à l'aide d'électroencéphalographie.

Cette thèse se concentre sur la séparation de l'IV en 3 composantes par Kilteni et al. [KGS12] : le SoA, le SoBO et le SoSL. Toutefois, la définition de l'IV évolue, avec l'intention de créer de nouveaux questionnaires standardisés [PG21 ; RL20], et définir de nouvelles composantes de l'incarnation. En plus de ces 3 composantes, Peck et Gonzalez-Franco [PG21] ont également suggéré le contrôle moteur, les sensations tactiles, l'apparence externe et la réponse à un stimulus externe, faisant écho aux catégories de mesures de l'incarnation de De Vignemont, à savoir les mesures spatiales ("l'espace entourant l'objet incarné est-il traité dans l'espace péripersonnel"), des mesures motrices (a-t-on l'impression que l'objet incarné "obéit directement à sa volonté" – similaire au SoA) et des mesures affectives (l'objet incarné est-il "protégé des situations dangereuses" – déjà évaluées avec la réponse galvanic de la peau mais pas avec des questionnaires) [Vig11]. De même, Roth et Latoschik [RL20] ont suggéré une nouvelle dimension de l'incarnation consistant à la modification de la perception du schéma corporel.

D'autres expériences devraient être réalisées dans des scénarios de RV plus réalistes, comme dans les travaux de Fribourg et al. [Fri+18] (frapper un sac de frappe, un ballon de football, suivre un mouvement de fitness, sans interaction avec l'environnement ou une tâche de marche avec des obstacles à éviter). En effet, outre les expériences contrôlées, la RV est également destinée à être utilisée dans la vie réelle, dans des scénarios non contrôlés, et il est important d'étudier l'incarnation virtuelle dans des scénarios réalistes. L'impact des différents facteurs pourrait changer en fonction du type de tâche, et il est important de mieux comprendre si c'est le cas ou non. Nous pensons que les multiples scénarios réalistes et variés proposés par Fribourg et al. [Fri+18] constituent une bonne base. On pourrait aller plus loin en proposant une standardisation des scénarios en RV

pour avoir une bonne représentation de l'incarnation virtuelle et favoriser la comparabilité entre les expériences.

Dans le contexte des scénarios de RV réalistes, on peut se demander si l'étude du SoSL est pertinente. Cependant, il est toujours important d'en tenir compte dans l'étude de l'incarnation (en général et dans son application à la RV) pour mieux comprendre ce phénomène. En plus des scénarios RV, un guide méthodologique pour une incarnation virtuelle optimale aurait été intéressant à proposer au cours de cette thèse. Bien que cela n'ait pas été envisagé, nous pensons qu'il y a encore trop de domaines à explorer sur l'incarnation virtuelle pour avoir des règles et établir un guide. Cela reste néanmoins une possibilité d'étude future.

Pour résumer, il y a encore de nombreuses pistes à explorer à la suite de cette thèse. Galileo Galilei disait *“Mesure ce qui est mesurable, et rend mesurable ce qui ne peut être mesuré”*. Cette thèse tente d'avancer dans cette direction. Nous espérons que cette thèse aidera la communauté RV à mieux comprendre l'incarnation et son évaluation en RV, qu'elle fournira une base expérimentale pour de futures études et qu'elle apportera de nouvelles connaissances sur l'interaction entre le SoA, le SoBO et le SoSL.

Titre : Évaluation et Manipulation de l'Incarnation Virtuelle

Mot clés : Réalité virtuelle, avatars, sentiment d'incarnation, expérience utilisateur

Résumé : La réalité virtuelle consiste à immerger un utilisateur dans un monde virtuel et lui permettre d'interagir en temps réel avec le contenu de celui-ci. Dans ce monde, l'utilisateur peut être représenté par un corps virtuel appelé un avatar et avoir l'impression que cet avatar est son propre corps. C'est ce qu'on appelle l'incarnation virtuelle (IV), caractérisée par 3 composantes : le sentiment de localisation, d'agentivité et de possession de corps. L'IV peut modifier la perception du corps d'un utilisateur ou son comportement. Néanmoins, l'évaluation de l'IV est compliquée, étant un phénomène subjectif. Le consensus actuel est d'utiliser des questionnaires standardisés mais ceux-ci ne peuvent être réalisés qu'a posteriori et non en continu, et cela force l'uti-

lisateur à effectuer une tâche supplémentaire. Cette thèse se concentre sur deux axes. Le premier est l'étude de l'interaction entre les composantes de l'IV. En effet, leur interdépendance et leur importance relative n'est pas encore claire. Dans une expérience utilisateur, nous tentons de manipuler chaque composante indépendamment afin de permettre de mieux évaluer l'IV. Cette étude ouvre la voie à de futures expériences. Le second axe est la recherche de marqueurs neurophysiologiques du sentiment d'agentivité à l'aide d'électroencéphalographie (EEG). En analysant des signaux EEG de Jeunet et al. 2018, nous cherchons à obtenir une évaluation en temps réel de ce sentiment comme alternative aux questionnaires.

Title: Evaluation and Manipulation of Virtual Embodiment

Keywords: Virtual reality, avatars, sense of embodiment, user study

Abstract: Virtual reality consists of immersing users in a virtual environment (VE) and allowing them to interact in real time with the content of it. In this VE, users can be represented by a virtual body called an avatar and feel this avatar to be their own body. This is called virtual embodiment (VEmb), characterised by three components: the senses of self-location (SoSL), agency (SoA), and body ownership (SoBO). VEmb can alter the perception of a user's body or their behaviour. However, the evaluation of VEmb is complicated, being a subjective phenomenon. The current consensus is to use standardised questionnaires, but these can only be conducted retrospectively and not continuously, and forces users to per-

form an additional task. This thesis focuses on two areas. The first is the study of the interaction between the components of VEmb. Indeed, it is not yet clear how the three components interact with each other or whether one component is more important than the others. In a user study, we try to manipulate each component independently to allow a better evaluation of VEmb. This study paves the way for future experiments. The second axis is the search for neurophysiological markers of the SoA using electroencephalography (EEG). By analysing EEG signals from Jeunet et al. 2018, we try to obtain a real-time assessment of this feeling as an alternative to questionnaires.