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Par

« Rebecca FRIBOURG »

« Contribution to the Study of Factors Influencing the Sense of Embodiment Towards Avatars in Virtual Reality »

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Rapporteurs avant soutenance :

Ronan Boulic	Maître d'Enseignement et de Recherche, EPFL
Catherine Pelachaud	Directrice de Recherche CNRS, ISIR

Composition du Jury :

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Examinateurs :	Victoria Interrante	Professeure, Université du Minnesota
	Guillaume Moreau	Professeur, Ecole centrale de Nantes
	Mel Slater	Directeur de Recherche, Université de Barcelone
Dir. de thèse :	Anatole Lécuyer	Directeur de Recherche, Inria Rennes
Co-encadrants. de thèse :	Ferran Argelaguet	Chargé de Recherche, Inria Rennes
	Ludovic Hoyet	Chargé de Recherche, Inria Rennes

To my Dad

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Table of Contents

List of Figures

List of Tables

Author’s List of Publications

Journals

- **Fribourg, R.**, Ogawa, N., Hoyet, L., Argelaguet, F., Narumi, T., Hirose, M., & Lécuyer, A. (2020). Virtual Co-Embodiment: Evaluation of the Sense of Agency while Sharing the Control of a Virtual Body among Two Individuals. *IEEE Transactions on Visualization and Computer Graphics.*
- **Fribourg, R.**, Argelaguet, F., Lécuyer, A., & Hoyet, L. (2020). Avatar and Sense of Embodiment: Studying the Relative Preference Between Appearance, Control and Point of View. *IEEE Transactions on Visualization and Computer Graphics, 26(5), 2062-2072.* **Best TVCG Journal Paper Award**.

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- **Fribourg, R.**, Argelaguet, F., Hoyet, L., & Lécuyer, A. (2018, March). Studying the sense of embodiment in VR shared experiences. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 273-280). IEEE.

National and International Communications

- **Fribourg, R.**, Talk on Users Preferences over Appearance, Control and Point of View on the Sense of Embodiment, *WACAI Workshop on the “Affects, Artificial Companions and Interactions”, 10 septembre 2020 (to be presented) (Virtual).*
- **Fribourg, R.**, Talk on the Importance of Control on Avatar Sense of Embodiment, *GTAS (Working group on Animation and Simulation) Days, Friday 10th of July (Virtual)*

- **Fribourg, R.**, Talk on Avatars and Virtual Shared Environments, *Person-to-person interactions Workshop June 25th 2020 (Virtual)*
- **Fribourg, R.**, Poster presentation on Avatars and Virtual Shared Environments, *VERE Symposium "Virtual and Robotic Embodiment – from neuroscience to virtual reality and robotics", 28th February – 1st March, 2019, Barcelona.*
- **Fribourg, R.**, Talk on Virtual Embodiment and Acceptability, Technoférence n°27: Augmenter l'humain, solutions et adoption (Nantes, France, janv. 2019).
- **Fribourg, R.**, Talk on Avatars and Virtual Shared Environments, *13èmes Journées de la Réalité Virtuelle (Evry, France, Octobre 2018).*

Others

- A. Audinot, D. Dewez, G. Fouché, **R. Fribourg**, T. Howard, F. Lécuyer, T. Luong, V. Mercado, A. Reuzeau, T. Rinnert, G. Vailland, F. Nouviale, F. Argelaguet, "3Dexterity: Finding your Place in a 3-Armed World", *IEEE 3D User Interface Contest 2020*, **Best 3DUI Demo Award – Honorable Mention**
- H. Brument,**R. Fribourg**, G. Gallagher, T. Howard, F. Lécuyer, T. Luong, V. Mercado, E. Peillard, X. de Tinguy, M. Marchal, "Pyramid Escape: Design of Novel Passive Haptics Interactions for an Immersive and Modular Scenario", *IEEE 3D User Interface Contest 2019*, **Best 3DUI Demo Award**
- A. Bernardin, G. Cortes, **R. Fribourg**, T. Luong, "Toward Intuitive 3D User Interfaces for Climbing, Flying and Stacking", *IEEE 3D User Interface Contest 2018*, **Best 3DUI Demo Award – Honorable Mention**

> *"Letters are symbols. They are building blocks of words which form our languages. Languages help us communicate. Even with complicated languages used by intelligent people, misunderstanding is a common occurrence. We write things down sometimes — letters, words — hoping they will serve us and those with whom we wish to communicate. Letters and words, calling out for understanding."*
>
> Log Lady - Twin Peaks

1

Introduction

This thesis, titled **"Contribution to the Study of Factors Influencing the Sense of Embodiment Towards Avatars in Virtual Reality"**, presents research that aims to enhance the experience of being embodied in an avatar in virtual reality by better understanding how users perceive their avatar through their sense of embodiment.

1.1 Did you say "avatars"?

I like to use the phrase "happiness only real when shared" from the American hiker Christopher McCandless, to justify that one of my greatest pleasures in doing research comes from being able to share it with others. Yet, talking about one's own research to a wider audience is challenging in that one must tailor one's explanation to a specific public whom knowledge regarding the research topic can vary and who may even already have misconceptions about it. For instance, something that I got to notice throughout the three years of my PhD, is that when mentioning my thesis topic, "avatars", I would often face people repeating the word slowly: "avatar. . . ", trying to figure out what that word evoked in their mind. Most of the time, people have a very different image of avatars: "my profile picture on facebook", "my character when

I play video games", or even the technologically revolutionary movie from James Cameron [1]. Overall, while an avatar always seems to be highly related to the self, it can be many different things depending on the context, which is why it is important to define the frame of reference within which we consider avatars: in this thesis, we are interested in avatars in the context of Virtual Reality (VR).

Talking about VR also often triggers interesting reactions, as the association of the two words "Virtual" and "Reality" tends to intrigue people. Yet, if they may first appear as oxymoron, their definitions are not incompatible. Combined together, the two words refer to a distinct concept whose definition remains under the influence of its novelty: in flux. In this manuscript, we refer to the following definition of Arnaldi et al. [2003].

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." [Arnaldi et al. 2003]

Since the early years of VR, research has been conducted to create virtual content in which users can experience a simulated and virtual world as if it were real. In order to provide such an illusion, various visual, auditory or haptic stimuli are provided by the simulation in reponse to users' actions [Sherman and Craig 2003]. The congruence between all these stimuli and users' actions, also referred to as "sensorimotor contingencies" [Kaspar et al. 2014], strongly characterizes the immersion experienced in VR. This is reflected for instance by changing the visual display accordingly to user's head movements [Slater 2009]. In addition, users' level of immersion also depends on the visual display systems used to provide the simulation, such as projection-based systems (e.g. Cave Automatic Virtual Environment, better known by the recursive acronym "CAVE") and Head-Mounted Displays (HMDs) (see Figure 8.2). In the last years, consumer-grade HMDs have become more and more available, leading to a wide spread of VR applications developped for such equipment in which users can be immersed with a total visual occlusion of the physical world. This particularity of HMDs to fully hide the physical world provides the groundwork for this thesis: when users wear an HMD, they cannot see their physical body anymore.

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[1] Cameron, James, et al. *Avatar*. 20th Century Fox, 2010.

Figure 1.1 – Examples of the two main visual display systems to experience VR. Left: A user immersed in the Cave Immersia in Rennes, France. Right: A man uses an HMD and joysticks at the MCR offices in Lille, France. Philippe Huguen / AFP - Getty Images file

In the physical world, our body is a natural point of reference that enables us to situate ourselves spatially in the surrounding environment. Yet when we are immersed in VR with HMD-based systems, we lose the visual information of our physical body in the process. While the sense of self-movement and body position, also known as proprioception, gives us cues regarding the position of different parts of the body [Tuthill and Azim 2018], executing precise interactions that involve the body remains challenging without visual feedback of the body. This has taken on all the more importance due to VR's objectives of providing realistic and effective interactions with VEs. For this reason, questions related to the representation of users in the Virtual Environment (VE) have become more and more important in the last years. This user's representation in the VE is commonly referred to as an "avatar".

1.2 Avatars in Virtual Reality

While the term "Avatar" is also defined in numerous ways, we refer to the general definition delivered by Sherman and Craig [2003]:

Avatar

"A virtual object used to represent a participant or a physical object in a virtual world; the (typically visual) representation may take any form." [Sherman and Craig 2003]

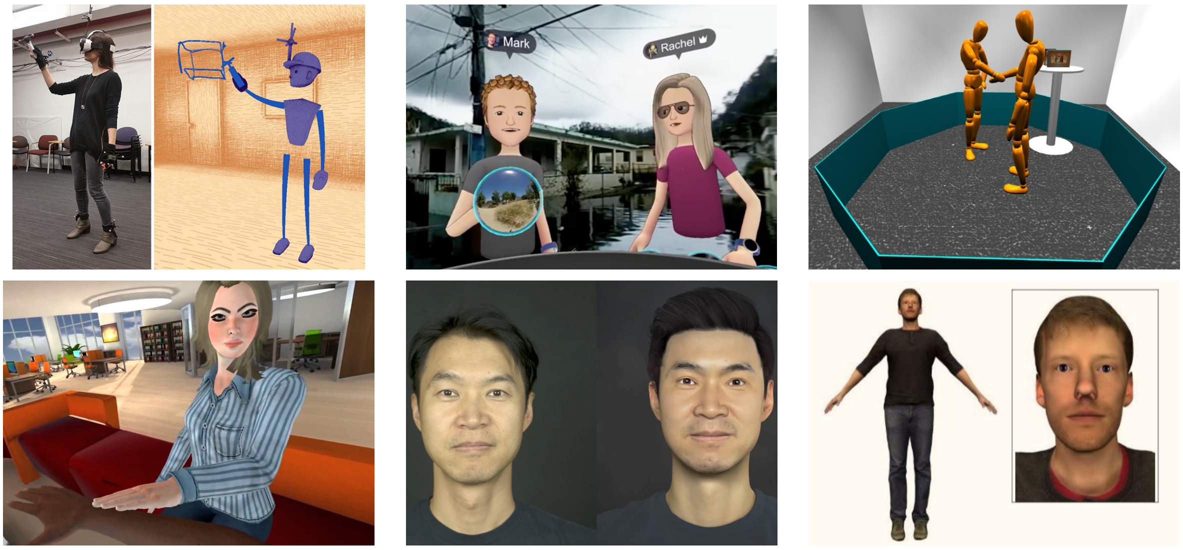


Figure 1.2 – Examples of different avatar representations. Top, left: A cartoonish avatar in Ken Perlin's Holojam virtual reality system. Photography by Sebastian Herscher; Holojam Artwork by David Lobser. Top, center: A cartoon Zuckerberg, with Facebook's head of social virtual reality, Rachel Franklin, on a flooded street. Photography by Facebook. Top, right: Puppet avatar from Roth et al. experiment [2016]. Bottom, left: Realistic avatar from the beingavatar project, bottom, center: ObEN co-founder Adam Zheng and his photorealistic avatar. Bottom, right: Full-body scanned avatar and face scanned from Latoschik et al.[2017].

This definition is particularly interesting as it combines two important points: first, an avatar always represents a physical entity, either a person (most commonly) or an object. Therefore, a virtual character controlled by an artificial intelligence cannot be defined as an avatar in the context of this definition. Second, while recent research has led to the creation of high-quality anthropomorphic avatars, it is important to keep in mind that an avatar can have any kind of representation, from very abstract (e.g., geometric representation of some body parts) to very realistic (e.g., full body represented with anthropomorphic details) (see Figure 8.3). In the scope of this thesis, we focus on avatars in the context of immersive virtual reality using HMD-based systems. In such a configuration, users can fully embody their avatar, control it with their own movements and may experience it as if it were their own body. The process of being embodied in an avatar can be represented by a perception-action loop (see Figure 8.4). Users embody a virtual avatar through which they interact with the VE and its contents (i.e., virtual objects, other users, ect.). They receive multisensory feedback from these interactions that contributes to their experience of being embodied in the avatar.

The design of avatars must tailor to a number of technical and algorithmic constraints. For instance, giving avatars a realistic appearance requires demanding 3D model reconstruction, and giving users the possiblity of fluidly controlling their avatars with their own movements

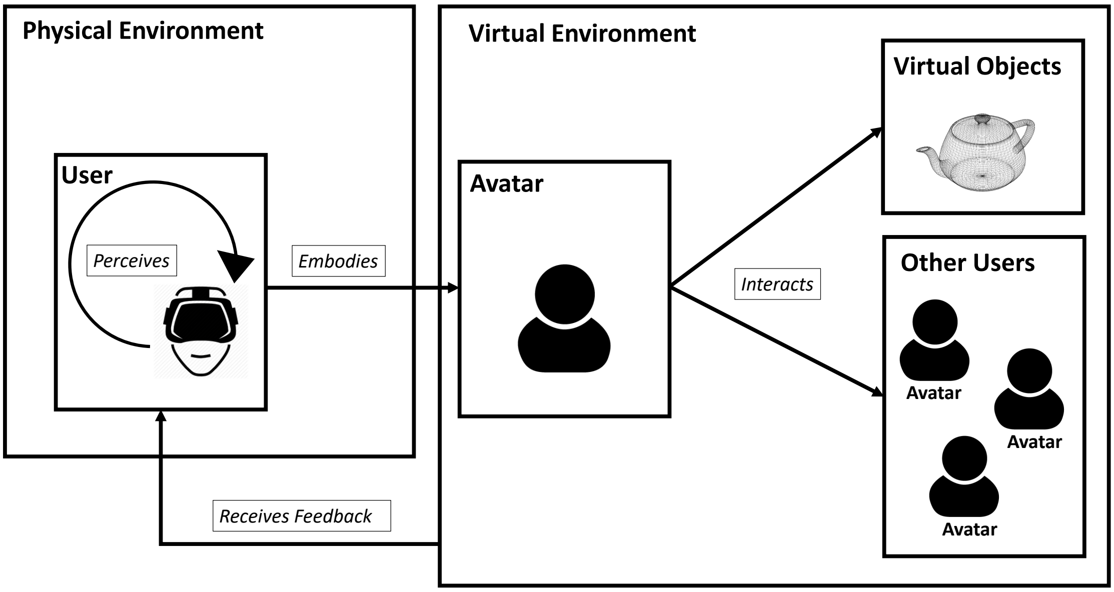


Figure 1.3 – Perception-Action loop involving avatars. Users from the physical world embody a virtual avatar that represents them in the VE. Through this avatar, they interact with the VE (either with virtual objects, or other users also represented by avatars). From this interaction, they receive feedback that they perceive and which contributes towards building their cognitive and subjective experience.

requires high level motion capture capabilities. In addition, complex algorithmic development is necessary to provide users with sensorimotor contingencies according to their interaction with the VE through their avatar. Achieving a fully functional avatar is therefore challenging because of technical limitations, but also because understanding the processes underlying the perception of avatars is difficult. Indeed, for users to interact realistically with the VE through their avatar, it is necessary that they "become one" with it, and feel that they own and can control this virtual body. This experience of the virtual body is commonly characterised by the Sense of Embodiment (SoE) [Kilteni, Groten, et al. 2012] and is widely studied in order to assess how users perceive their avatar and to which degree they accept or reject their virtual body.

In recent years, many studies have tried to better characterise and study the SoE in VR as a way to better assess how users perceive their virtual avatar. In 2012, Kilteni et al. [2012] introduced a decomposition of the SoE that was further used to study the SoE in a substantial body of research. According to them, the SoE refers to the feeling of being inside, controlling and having a virtual body, and can hence be decomposed into three respective and distinct subcomponents: the sense of self-location, the sense of agency and the sense of ownership. This decomposition has since extensively been used to better understand how users perceive their avatar. Nevertheless, the study of the SoE is challenging because of the difficulty of measuring a subjective feeling. Indeed, the SoE is a *quale* (i.e., a quality or property as perceived or experienced by a person), which makes it difficult to assess. For this reason, it has been necessary to explore the existing possibilities to measure and assess the SoE, in the context of user studies. Different methodologies were therefore explored in order to measure the subjective SoE. Among them, subjective questionnaires [González-Franco and Peck 2018] have found widespread use in embodiment studies, but other studies also tended to integrate objective measures such as as behavioral (e.g., implicit attitude changes [Banakou, Groten, et al. 2013]) and physiological (e.g., heart-rate [Meehan et al. 2002]) measures.

This research has provided valuable insights into the design of avatars in VR towards which users can achieve a high SoE. In addition, studies of the SoE have uncovered numerous novel possibilities for exploring the relation between body and mind [Kilteni, Groten, et al. 2012; Hoyet et al. 2016]. Avatars in VR enable original experiences as they can be altered and controlled in numerous ways. For example, it is possible to be embodied in avatars with a different gender [Peck et al. 2018] or with morphological changes such as a hand with six fingers [Hoyet et al. 2016]. Such experiences have helped to better understand own-body perception and have shown evidence of the plasticity of the brain in the case of altered body illusions. On the other hand, this research also gave valuable insights into how users perceive their virtual representation in VR and whether they are willing to accept a virtual body that differs from their own in terms of visual aspect and control schemes. In particular, applications in psychology and cognitive science have benefited from such findings in the past years, using for instance avatar embodiment as a tool for eating disorder therapies by embodying patients in virtual bodies of healthy subjects [Serino et al. 2019], or to sensibilize domestic violence offenders by changing their perspective towards the victim through avatar embodiment [Seinfeld et al. 2018]. The applications of avatars have now been widely spread to a very large range of fields, such as VR training, education, entertainment (e.g. immersive cinema), telemedecine, etc.

1.3 Factors Infuencing the Sense of Embodiment: From External to Internal

Overall, past studies on the topic have yielded many insights into how to design more efficient avatars in terms of embodiment. Different "factors of influence" emerged from this research, mainly in relation to the choices of design of the avatars as well as their technical characteristics.

For instance, the appearance of the avatar has been demonstrated to be a critical factor of influence in eliciting the sense of ownership [Argelaguet et al. 2016; Lin and Jörg 2016], while the control of an avatar seems to have a major impact on user sense of agency [Caspar et al. 2015]. Finally, the point of view can have an impact on where one perceives oneself to be located and thus alters the sense of self-location [Gorisse, Christmann, Amato, et al. 2017]. These studies have in common that they focus on factors that are only centered on the avatar: They mostly consider what might impact the perception of an avatar through its characteristics.

In this thesis, we suggest a categorization of the factors influencing the SoE that involves more than just the avatar itself. Indeed, as shown in Figure 8.4, an avatar is part of a loop that involves several additional elements: the user and the virtual environment potentially involving other users. Despite being an integral part of the avatar experience, characteristics related to the user (personality traits, gender, etc.) and the virtual environment (interactivity, multi-user capability, etc.) have rarely been considered in studies on the SoE. We therefore propose a representation where each layer represents a group of potential factors influencing the SoE (see Figure 8.5). Factors belonging to the Avatar and VE layer can be characterized as "external" factors, while factors related to the user can be characterized as "internal" factors. In this manuscript, we also use this representation to structure the research that has been conducted in the scope of this thesis.

1.4 Scope and Research Axes

Despite the notable insights from the previously discussed studies, grey areas remain in our understanding of how users perceive their avatar in VR. This in turn limits our ability to enhance these avatars in order to strengthen the quality of user experiences. In particular, our proposed representation of the factors influencing the SoE enabled us to identify several "gaps in the big picture", from which we extracted three main research axes, corresponding to the three layers of our factor representation. We then highlighted different research questions that we mapped on these layers:

- **Virtual Environment -** Can the virtual environment in which users are immersed impact users' SoE towards their avatar? And more precisely, does the presence of other users in the VE influence one's own SoE towards an avatar?
- **Avatar -** Is there a dominant contribution between the avatar-related factors of influence towards the SoE? Should some of these factors be prioritized in the creation of virtual avatars?

- **User -** Why are some people easily embodied in their avatar, while others are more reluctant to the experience? Do individual differences within users or personality traits influence the way the avatar will be perceived?

These axes of research are detailed in the following subsections, starting with the external layer of our representation: the virtual environment.

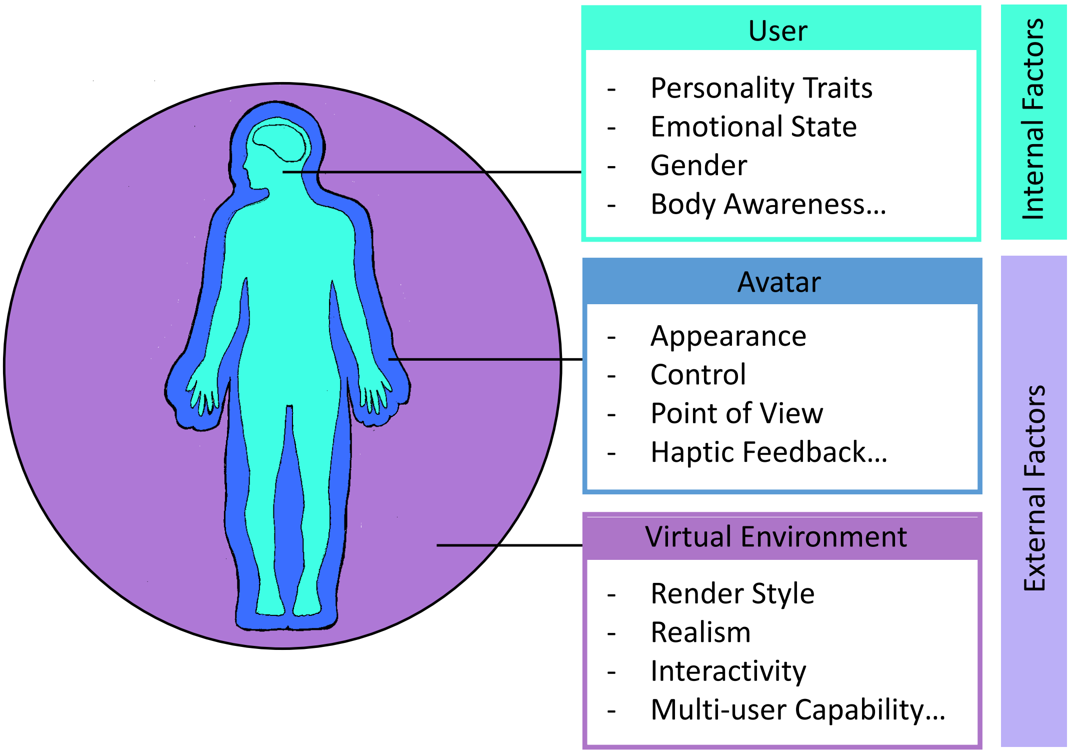


Figure 1.4 – Suggestion of representation of the factors influencing the SoE: each layer represents a group of factors: the User, the Avatar and the Virtual Environement.

1.4.1 Influence of the Virtual Environment (External Factors)

Virtual environments can be characterised through a multitude of facets, such as their render style or realism, their degree of interactivity and the amount of sensory feedback they provide. The characteristics of VEs are known to influence users' VR experiences and more precisely, to influence users' sense of presence, another *quale* that refers to “the feeling of being in the virtual world” [Schuemie et al. 2001]. However, the impact of the VE characteristics on the SoE remains rarely explored. In particular, we identified two aspects of the VE that are likely to influence the

SoE: the social dimension of VEs (i.e. the presence of other users sharing the same VE) and the introduction of threats towards the avatar in the VE.

1.4.1.1 Shared Virtual Environments

More and more high-quality shared VR experiences are now being released by VR developers. These configurations enable several users to be immersed in the same virtual environment without necessarily being physically co-located. They also have the possibility to simultaneously interact with each other and the virtual environment. Such progress has reinvigorated research interests in shared VEs, e.g. [Brown et al. 2017; Kuszter et al. 2014; Sharma and Chen 2014]. In order to assess the effect of such shared VEs on users' experience, the sense of presence has been intensively studied. It was demonstrated that seeing other users in the VE could be taken as an evidence of one's own existence in the VE, and could increase the sense of presence [Heeter 1992]. However, while the sense of presence was investigated in shared VEs, the studies of the SoE only seemed to focus on single-user experiences. It remains unclear how sharing virtual experiences with another user embodied in an avatar might influence one's own SoE. We therefore decided to explore this question in the thesis.

To this aim, we present a study exploring the influence of VR shared environments on users' own SoE in **Chapter 3**. We thus present an experiment in which two participants shared the same virtual environment and performed a task together that involved different degrees of competitiveness, and explore the effects on users SoE towards the avatar and engagement in the virtual task. In **Chapter 4**, we explore the context of VR shared environment one step further by investigating the influence of sharing a virtual avatar with another user. More precisely, we were interested in the sharing of the control of the avatar, and how the shared weight of control (that was modulated) would influence users own sense of agency and motor actions. This work was done in collaboration with Nami Ogawa, a visiting PhD student from the University of Tokyo. We both contributed equally to this research study.

1.4.1.2 Threat Occurrences in VEs

Another characteristic of VEs that is widely exploited is their capacity to make users go through a wide range of emotions. For this reason, VR has become especially attractive for different fields of research where it is crucial that the virtual environment succeeds in inducing emotional reactions. This involves research exploring user emotional reactions in VR [Diemer et al. 2015] as well as works investigating the use of virtual threats in VR-based exposure therapy to treat phobias [Wald 2004; Tardif et al. 2019]. Another field of research that interests us more specifically in this thesis, is the study of virtual avatar embodiment, where the introduction of a threat is frequently used to assess users SoE towards their avatar. More precisely, several studies successfully showed that the SoE was correlated with the reaction to a virtual threat towards the virtual body [Yuan and Steed 2010], validating the assumption that if users are well embodied in the virtual avatar, they will physically react to a virtual threat towards their virtual body. Nevertheless, while the introduction of a virtual threat in virtual embodiment studies is widely used, no research has specifically evaluated the impact of the virtual threat on the SoE. In other words, is the SoE modulated by the actual occurrence of the threat?

In **Chapter 5**, we therefore present a study investigating the potential impact of threat introduction on the SoE and do not consider threat introduction only as a measure, but as a factor likely to affect the SoE. This chapter also explores the little known impacts of threat repetitions on both threat response and the SoE.

1.4.2 Influence of the Avatar (External Factors)

In our second axis, we were interested in the interlayer of our representation: the Avatar. Studies exploring the influence of factors towards the SoE usually focus on one factor at a time and measure its influence on the SoE. Different factors of influence mainly related to the choices of design of the avatars as well as their technical characteristics emerged from this research. However, several concerns arise regarding the methodologies used to assess users' SoE in VR. First, such measures do not allow the assessment of inter-relations between the factors influencing the SoE. Indeed, if we start to better understand the influence of isolated factors on the SoE, we still have little information regarding the relative contribution of each factor towards the SoE, or regarding the user's preference for a factor over another while being embodied in an avatar. As for today, several questions remain open: Is there a dominant contribution between the factors of influence towards the SoE? Should some of these factors be prioritized in the creation of virtual avatars? The assessment of inter-relations is challenging in terms of experimental protocol due to the numerous potential factor combinations and because it usually needs between group designs which requieres a high amount of participants. For this reason, we were interested in this thesis in exploring new ways to assess users' SoE, and more specifically in a way that would allow the study of inter-relations within factors.

We present in **Chapter 6**, a study that we conducted to explore inter-relations within factors of the SoE. To do so, we applied the subjective matching technique for the first time in the context of embodiment studies in order to explore the relative preference between three factors related to the avatar: appearance, control, and point of view.

1.4.3 Influence of the User (Internal Factors)

Finally, our third axis is dedicated to the internal layer of our factor representation: the User. While most studies on avatar embodiment have been able to show general trends regarding the way "external" factors seem to influence the SoE, they did not consider the "internal" user state (e.g. personality or background experiences). However, the inter-user variability remains non-negligible. In practice, we can observe that some people easily believe in the virtual embodiment illusion, while others are on the contrary totally refractory. Initial research investigating the link between personality traits and the perception of VR experiences focused on the sense of presence [Wallach et al. 2010]. For example, it was found that agreeableness, a personality trait, was positively associated with spatial presence [Sacau et al. 2005]. More recently, some works explored the link between users' individual differences and the SoE. For instance, body awareness [David, Fiori, et al. 2014] and personality traits [Jeunet et al. 2018] have been studied in relation to the SoE. In this last one, Jeunet et al. showed that the sense of agency was correlated with the Locus of Control, another personality trait. However, in spite of the work by Jeunet et al. [2018], the majority of the works addressing such internal factors have mainly focused on users' SoE in the physical world. For this reason, we were interested in further investigating the influence of a wider range of personality traits and of body awareness on the SoE in VR.

In **Chapter 6**, we thus aim to provide the global knowledge regarding factors influencing the SoE by focusing on individual differences between users. We therefore explored the potential influence of personality traits and body awareness on the SoE. This work was done in collaboration with the former intern Diane Dewez. My contribution to this last study mainly concerned concept discussions, experimental design and partially writing of the paper.

“Every now and then one paints a picture that seems to have opened a door and serves as a stepping stone to other things.”

Pablo Picasso

2

Related Work: User Perception and Factors of Influence Towards Avatar in Virtual Reality

Abstract:

In this chapter, we present a review of the literature that paved the way for the research conducted in this thesis. We first present an overview of the literature about concepts related to the perception of avatars in VR: the sense of presence in virtual environments and related concepts, and the perception of one’s own body. We then focus on the perception of virtual bodies, i.e., avatars in the VR and present several works exploring the Sense of Embodiment in VR. Finally, we report several works investigating factors of influence towards the Sense of Embodiment, following the same structure as presented in our factors representation: Factors related to the VE, the Avatar and the User.

2.1 Introduction

As presented in the introduction of the manuscript, the work of this thesis was articulated around three categories of factors likely to influence the SoE: Avatar-related, VE-related and

User-related factors. The main goal of this state of the art is therefore to review the existing works that explored the factors influencing the SoE in each of these categories. In addition, the scope of this thesis is multidisciplinary in that it gathers both technological challenges (mostly investigated in computer science), but also perceptual challenges that relates more to the field of cognitive science. Therefore, we provide beforehand background concepts related to the perception of avatars in VR. More precisely, this chapter is organised as followed: First, we introduce the concept of VEs and their technical characteristics, and we approach the notions of presence in VEs as well as other related concepts. Second, we present general concepts of own-body perception, first in the context of the physical world, and then in the context of VR. We then narrow the focus by describing what is the Sense of Embodiment, its theory and the ways to measure it, and describe several works exploring how this sense can be elicited and modulated. Finally, we depict various studies exploring factors that influence the SoE, followinf the structure of the factors representation previously presented (see Figure 8.5).

2.2 Virtual Environments

"As if by magic...": One may believe that in some ways, the success of VR towards its public relates on its analogy with magic. What is sure is that both manipulate reality in order to provide illusory perceptions. While immersed in a VE, the illusion already begins by substituting the physical environment with a VE in which the user might believe or not. In this section, we first describe the technical features that constitute a VE, then we present several concepts related to the perception of VEs.

2.2.1 Technical Features of Virtual Environments

Slater refers to VR as "a medium in which people respond with their whole bodies, treating what they perceive as real." [Slater 2009]. A typical VR system provides users' head tracking that is used to compute the VE images according to users' head movement. With an HMD, the resulted left and right images for each eye ensure stereo vision of the three-dimensional VE, and users therefore have the illusion of moving in and being surrounding by the VE. Ideally, a VR system also provides tracking of users' body which enables them to effect changes in the VE, and encompasses multiple sensory displays (visual, auditory, haptic, etc.) to confer users feedback of these changes and of the global VE.

The congruence of all sensory displays with users' actions in the VE plays an important role in the quality of the VR experience. More precisely, each sensory display can be impacted by several factors which will modulate by extent the resulted immersion. Some of them were identified by Sanchez-Vives and Slater [2005]:

1. **Visual Display**: VE can ve experienced through different visual display systems: projected-based or through HMD. We are interested here in VE experienced through HMDs.
   - **Field-of-view:** The visual display can be more or less wide (typically around 100 degrees diagonal for an HMD nowadays, compared with 180 degree horizontal and 120 degree vertical for normal vision.)
   - **Resolution:** The visual display may have more or less number of pixels per unit projected visual area.
   - **Frame-rate:** The number of frames the computer can deliver per second. If the VE is particularly complex, the computational load required to render it my lead to a lower frame-rate, and by extent to discontinuities in the image motion. This contributes to the system latency.
2. **Auditory feedback:** There can be an ambient sound in the VE that coincides with what is visually displayed, as well as specific auditory feedback to actions performed in the VE.
3. **Haptic feedback**: VR systems can also provide haptic feedback (e.g., through a joystick held in the users' hands, that would vibrate when it collides with a virtual object).
4. **Latency:** It designates the time between the initiation of an event in the VE by a user, and the time that the system responds.

Sanchez-Vives and Slater [2005] state that all these factors define what is called "immersion". More precisely, they define immersion as "an objective property of a system that in principle can be measured independently of the human experience that it engenders". Although related, they therefore differentiate it from the subjective experience of being immersed in a VE.

2.2.2 Presence and Related Concepts

In order to understand how to design VEs in a way that provides efficient immersion to users in VR applications, it is necessary to be able to assess how participants respond such to VEs [Slater, Spanlang, and Corominas 2010]. Several theories and concepts have emerged in the last years with the aim of defining and categorizing the subjective experience of being immersed into a VE. We present hereafter the main concepts that have been studied in order to assess such subjective experience: Presence, Place Illusion and Plausibility Illusion.

2.2.2.1 Presence

The concept of presence, originally developed in the early 1990s [Sheridan 1992], has for many years been thought to provide a measure of the subjective experience of "being" in a virtual environment, independently of the applications or systems [Slater, Spanlang, and Corominas 2010; Schuemie et al. 2001]. According to Sanchez-Vives and Slater [2005], an evidence of such experiences relies on the observation of users behaving in the VE the same way as if they were in the physical world. Based on this statement, a core of research investigated different means to assess how users respond to the VE, and therefore evaluate their sense of presence. Among them, the use of subjective questionnaires (e.g., the one proposed by Usoh et al. [2000]) has been greatly employed to evaluate the subjective experience of presence, but is also often completed with objective measures as behavioral (e.g., implicit attitude changes [Banakou, Groten, et al. 2013]) and physiological (e.g., heart-rate [Meehan et al. 2002]) measures. Many works tended to understand which factors may enhance or reduce the sense of presence in VR. In that vein, Slater et al. [1995] were of the firsts to propose that immersion affected the sense of presence, where immersion refers to *"the extent to which the computer displays are extensive, surrounding, inclusive, vivid, and matching"* [Bulu 2012]. Additionally, Witmer and Singer [1998] considered involvement as another factor impacting the sense of presence, stating that higher degree of involvement and immersion in a virtual environment would lead to a higher sense of presence.

2.2.2.2 Place illusion and Plausibility Illusion

In 2009, Slater [2009] proposed a deconstruction of presence into two orthogonal components: Place Illusion (PI) and Plausibility Illusion (Psi). This decomposition responds to the fact that the sense of presence on its own does not consider possible loss of credibility of the VE and how it may affect the plausibility of the experience for the users. The plausibility of the VE was therefore clearly dissociated from the sensation of "being there" and considered as Psi, while the sensation of "being there" initially associated to the sense of presence was considered as PI. In more detail, Psi was designated to be "the extent to which the system is programmed to produce correlations with the behavior of the participant, how much events in the VE refer personally to the participant, and the overall credibility of the scenario (in particular in relation to how a similar situation might be in physical reality)" [Slater, Spanlang, and Corominas 2010]. An interesting point in the framework proposed by Slater [2009] is also the consideration of users' avatar as a fusion of PI and Psi: the fact that users can see a virtual body when they look down towards their body the same way as they would see their own body in the physical world, is hence also considered as critical aspect of the realness of the VE.

2.3 Own-Body Perception

Within the scope of this thesis, we are interested in the capacity of VR to provide illusory body perception through "virtual embodiment", i.e. the process of putting a user into a virtual body. In order to comprehend the concepts related to virtual embodiment, it is necessary to understand beforehand some initial notions of body perception and self-perception.

2.3.1 Bodily Self-Consciousness

"What is it like to have a body?", questionned Longo et al. [2008] while investigating the structure of bodily self-consciousness. The ability of distinguishing one's self body from other bodies or objects in the surrounding environment has been in the spotlight of many research in the areas of philosophy, psychology and neuroscience [Ghallager 2000; Jeannerod 2003]. As stated by Costantini [2007], perceiving one's own body is a completely different experience from others' body perception. It is a "continuous feeling that the body belongs to us and that we continuously identify with our own body". According to Mandrigin and Thompson [2015], own-body perception is a type of "bodily self-awareness", and therefore, by perceiving our body as our own, we are aware of our bodily self. What is the process underlying such perception of one's own body? The human brain continuously receives information from what can be defined as bodily events. Such information can be received either by "interoception" or "exteroception" [Costantini and Haggard 2007]. Interoception refers to the events received from organs inside the body while exteroception refers to information gathered from the external environment through multiple sensory (vision, touch, auditory, olfaction, and gustatory). More precisely, this process of sensory assessment is commonly referred to as "multisensory integration" [Stein and Stanford 2008].

2.3.2 Altered Body Perception

In the process of multisensory integration, it is also stipulated that the congruence between all the sensory inputs contributes to a higher response from the brain in the experience of owning a body [Kokkinara and Slater 2014]. Accordingly, discrepancies in the multisensory integration might lead to altered body perception. Such alterations may occur for instance in case of brain lesions or limb amputation. The existence of such neurological conditions have been valuable in order to investigate the perception of one's own body. For instance, a famous example of

Figure 2.1 – Demonstration of mirror box therapy for phantom limb pain developed by Ramachandran [1995].

altered body perception is the phenomenon of phantom limbs experienced by amputees. In such situations, patients have the sensation that their limb is still attached to their body, and might even feel pain from it. Interestingly, it was found that when these patients see the reflection of their non missing limb in a mirror, along with tactile stimulation of this limb, they could experience the feeling of touch towards the missing limb, and have their feeling of pain reduced [Ramachandran et al. 1995] (see Figure 2.1). While these studies brought valuable insights regarding own-body perception, the variability and concurrence of the deficits in patients with impairments makes it difficult to understand and generalize the precise role of own-body perception in everyday experience [Costantini and Haggard 2007]. Therefore, another core of research tried to investigate altered body perception on healthy subjects, where controlled experimental settings are used to provide subjects with an "illusory" body perception. In particular, the bodily self-consciousness has been investigated using body ownership illusions that enable to identify to which extent we can integrate external objects has being part of our body.

2.3.3 Body Ownership Illusion

A famous example of body ownership illusion is the Rubber Hand Illusion (RHI) [Botvinick and Cohen 1998], in which participants experience an artificial limb as part of their own body. In the experiment, one arm of the participants is hidden and a rubber hand is placed in an anatomically plausible position in front of the participants (see Figure 2.2). It was shown that synchronous stroking on the participants' hidden hand and the aligned rubber hand could results in an illusion of ownership towards the rubber hand.

In order to assess the extent to which participants experienced the rubber hand as their own, participants of Botvinick and Cohen's experiment [1998] were requested to answer a subjective

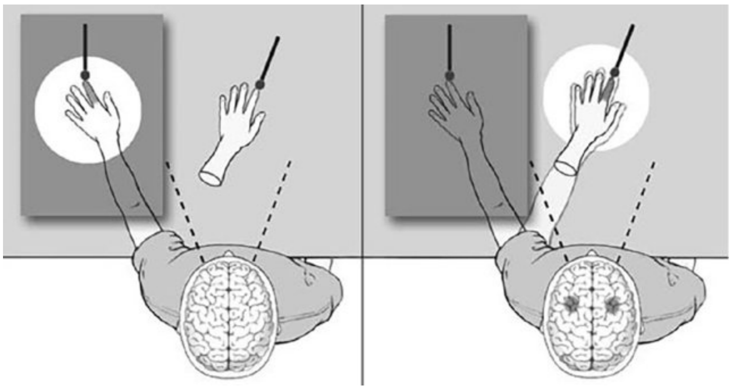


Figure 2.2 – The rubber hand illusion setup [Metzinger 2009]. The illustration on the left shows the set up of the RHI before the illusion occurred. The illustration on the right shows the subject's illusion while the rubber hand is being stroked synchronously with the left arm. Dark areas on the brain show areas of heightened activity in the brain during the illusion, and the phenomenally felt illusionary position of the arm is indicated by the white contour around the rubber hand. Figure by Litwak illustrations studio, 2004.

questionnaire in which they had to describe their experience and affirm or deny nine perceptual effects (see Table 2.1). Participants precised their response on a 7-point Likert scale ranging from 'agree strongly' (+ + +) to 'disagree strongly' (- - -). In a complementary experiment, Botvinick and Cohen [1998] probed for an objective measure of the ownership illusion. They found that after a prolonged exposure to the rubber hand, when participants were asked to indicate with their right finger and eyes closed where they estimated that their hidden arm was, the showed position was displaced towards the rubber hand, and the magnitude of the displacement correlated to the reported duration of the illusion. In addition, this effect was diminished when a small asynchrony was introduced between the brushing of the two hands, which was itself correlated to a reported low subjective ownership illusion. Another objective measure of the ownership illusion has been explored by Armel et al. [2003], who were among the first ones to show that response to a threat towards a rubber hand was linked to the assimilation of the rubber hand as into one's own body image. The threat response was in that case assessed by skin conductance response (SCR), e.g., if the rubber hand was "injured", participants displayed a higher skin conductance. These studies hence provided a worthwhile method to investigate the notion of own-body part perception, showing that it is possible to feel ownership towards a fake external body part, and that it can be assessed both subjectively and objectively. However, the experimental limitations of such setup do not enable the exploration of "full body illusions" but only body-parts ownership illusions. In addition, the RHI investigates body perception in a passive context: participants do not move their arm. For this reason, VR has been used in order to further investigate the aspects of body ownership illusions that were raised by studies as the RHI.

Table 2.1 – Questionnaire from Botvinick and Cohen’s study [1998].

It seemed as if I were feeling the touch of the paintbrush in the location where I saw the rubber hand touched.
It seemed as though the touch I felt was caused by the paintbrush touching the rubber hand.
I felt as if the rubber hand were my hand.
I felt as if my (real) hand were drifting towards the right (towards the rubber hand).
It seemed as I might have more than one left hand or arm.
It seemed as if the touch I was feeling came from somewhere between my own hand and the rubber hand.
I felt as if my (real) hand were turning “rubbery”.
It appeared (visually) as if the rubber hand were drifting towards the left (towards my hand).
The rubber hand began to resemble my own (real) hand, in terms of shape, skin tone, freckles or some other visual feature.

2.4 Own-Body Perception in Virtual Reality

Going back to the question of Longo et al. [2008] previously introduced, we may wonder in the context of own-body perception in VR: *“What is it like to have a **virtual** body?”* In this effusion of exploration towards the perception of one’s own body, VR rapidly became a targeted tool to overcome the limitations of initial physical setups as the one of the RHI. As mentioned by Ford Morie, when a user enters a VE, he has the simultaneous perception of two distinct bodies *“whether there is a virtual body image or whether there is direct or interpreted mappings of navigation movements”* [Morie 2007]. However, we can wonder if it is possible to experience the same sensations across a virtual body in an immersive VE as we would experience them through the biological body. Slater et al. [2008] were the first ones to transpose the rubber-hand illusion in VR. They showed that participants can experience body ownership towards the virtual arm, and that they react similarly to a virtual threat as participants reacted to threats towards the rubber hand. Not long after, multiple works explored the possibility of feeling ownership towards a whole virtual body [Maselli and Slater 2013; Petkova, Björnsdotter, et al. 2011], showing the importance of seeing the virtual body from a first-person point of view in order to provide a consequent ownership illusion.

In such research, the interest was greatly focused on humanoid virtual body, that resemble user’s physical body. However, a very interesting specificity of virtual bodies is that they can be altered in numerous ways to assess changes in user’s behavior and perception towards the altered virtual body. It becomes possible to control the realism [Petkova and Ehrsson 2008], the shape [Piryankova et al. 2014] or even the morphology of the avatar [Hoyet et al. 2016]. For instance, in this study from Hoyet et al., participants could experience what it would be like to have a hand with 6 fingers, and the illusion was such that participants did believe during the experiment that the sixth finger belonged to them (see Figure 2.3). Similarly, Steptoe et al. showed that it was possible to feel ownership towards an original extra body part: a virtual human tail [Steptoe et al. 2013].

Overall, we see that the plasticity of virtual bodies enable to control many parameters regarding the virtual body, likely to influence users' perception of the altered virtual body. The experience of a virtual body was usually assessed and characterized by the study of the feeling of ownership towards the avatar. Yet, another qualia started to be used to characterize the experience of being inside a body, namely, "the Sense of Embodiment (SoE)". In this thesis, we used this process of studying the SoE in order to assess user's perception of their avatar, which is why we dedicate the following section to the definition and theory of the SoE.

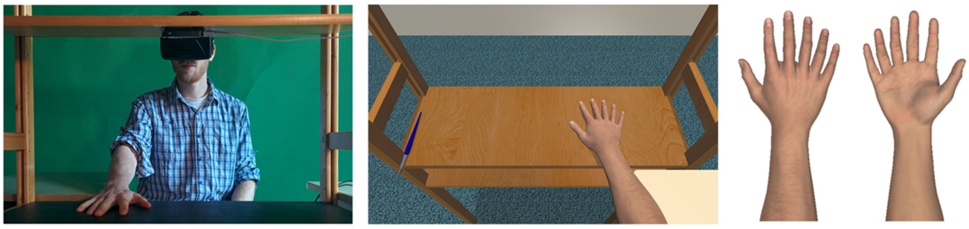


Figure 2.3 – Illustration of the six finger illusion of Hoyet et al study [2016]. Participants' see in the VE six-finger hands replacing their real hands tracked by a Leap motion tracker.

2.5 The Sense of Embodiment

For a long time, the SoE has remained undefined and the relation between the SoE and the sense of ownership was left unclear. As stated by de Vignemont [2011], this relation has been conceived in three different ways: one saying that they are synonymous, one saying that their are in opposition (ownership would consist in self-attribution of the body while the SoE would refer to self-localization [Lopez, Halje, et al. 2008]), and one stating that the sense of ownership is part of the SoE among other experiences [Longo, Schüür, et al. 2008]. Before defining the SoE, it is important to differentiate it from the terms "embodiment' or "virtual embodiment". According to de Vignemont [2011], embodiment can be defined as such: *E is embodied if and* *only if some properties of E are processed in the same way as the properties of one's body*. The SoE in contrast, corresponds to the associated phenomenology, in other words, the way embodiment is perceived. The SoE was further defined by Kilteni et al. [2012], which stipulates that SoE refers to the "ensemble of sensations that arise in conjunction with being inside, having, and controlling a virtual body". According to Kilteni et al. [2012], this complex phenomenon that is the SoE can be subdivided into three dimensions: the sense of self-location, the sense of agency and the sense of body ownership, which is a similar division as the one proposed by De Vignemont [2011] in three main dimensions (Spatial, Motor and Affective). To this day, there are still other representations proposed, as the one from Roth et al. [2017] who suggested an "Alpha IVBO" scale (where IVBO stands for "Illusion of Virtual Body Ownership"), in which they considered three subcomponents: Acceptance, Control and Change to measure IVBO. However, in this thesis we decided to use the definition of Kilteni et al. [2012].

2.5.1 The Sense of Ownership

The sense of ownership can be described as one's self-attribution of a body [Tsakiris, Schütz-Bosbach, et al. 2007] and therefore has a possessive character. As stated by Braun et al. [2018], its meaning can show through sentences as "This is *my* hand" or "*I* am the one who is having this feeling". In addition, the sense of ownership can be considered for a single limb as it was shown for the RHI or for an entire body. A number of studies have explored how ownership could be elicited, from which two categories of factors were identified: bottom-up and top-down factors [Tsakiris 2010].

Top-down factors refer to the cognitive processes that accompany the processing of sensory stimuli [Kilteni, Groten, et al. 2012]. More precisely, the degree of morphological similarity between the real and virtual body can be considered as a cognitive influence towards the sense of ownership. For instance, several studies showed that the sense of ownership towards an external object was diminished if it did not resemble the biological arm or hand of participants [Armel and Ramachandran 2003] or if it had a different spatial configuration [Costantini and Haggard 2007]. In VR, avatars can be highly anthropomorphic, and therefore resemble consequently participants biological body. For this reason, anthropomorphism can also be considered as a top-down factor of the sense of ownership [Lugrin, Latt, et al. 2015].

Bottom-up factors refer to sensory information, such as visual, tactile or proprioceptive stimuli. More precisely, the induction of a sense of ownership towards a body depends greatly on the synchronicity of multimodal stimuli. For example, Botvinick et al. [1998] showed that synchronous visual and tactile stimuli can elicit the illusion of the ownership of a fake limb

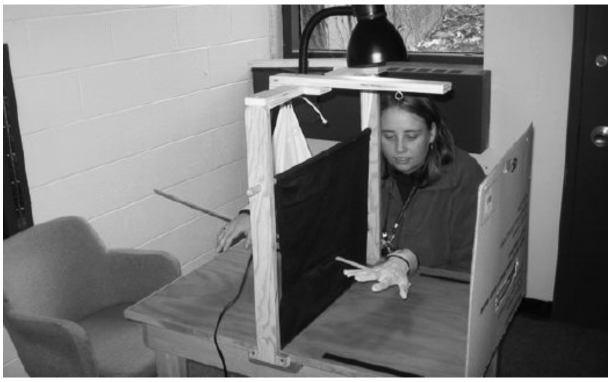


Figure 2.4 – Photograph of the apparatus used for the synchronous visuo-proprioceptive movement conditions in Dummer et al. [2009] study. The rubber hand is attached to a wood stick that can be moved by the experimentator.

(rubber hand) into one's body representation. Interestingly, according to [Lloyd 2007], the strength of the RHI is such, that it can be elicited in less than fifteen seconds in a majority of the population. In addition, if there is a discrepancy between the tactile and visual stimuli that does not exceed 300 milliseconds, the illusion can still be elicited. The importance of proprioception has also been exploited regarding its contribution to elicit a sense of body ownership. Indeed, another bottom-up factor of the sense of ownership consists in visuomotor synchronicity. In that line, Dummer et al. [2009] further examined the RHI with conditions of movement. The illusion of ownership was reported higher when visual movement of the rubber hand and felt movement were synchronised. Yet, the set up of such study is limited for that the experimenter has to control the movement of the rubber hand to modulate synchronicity with participants movements. VR on that regards gives the possibility to provide synchronous visuomotor feedback with the use of body tracking systems. Sanchez-Vives et al. [2010] exploited this medium opportunity and showed that the sense of ownership was modulated by the synchronicity of visuomotor feedback of the virtual hand. Visuomotor correlation was also found to be highly influential over another subcomponent of the SoE, directly related to own's own actions and movements: the sense of agency.

2.5.2 The Sense of Agency

The sense of agency can be described as a motor activity control, and refers to the fact of experiencing an action, intention or selection toward a body. When proprioception is defined as the sense *"that people know where the parts of their body are"*, the sense of agency could be defined as the sense that people have of knowing which action they can do, which control they have over this body and to which extent [Blanke and Metzinger 2009]. In the fields of philosophy and psychology, the sense of agency is considered to form a fundamental aspect of self-awareness together with the Sense of Ownership [Ghallager 2000]. Therefore, numerous studies on the sense of agency have been conducted in the fields of philosophy and psychology to examine human consciousness. Although the mechanisms of human consciousness are still not fully understood, two influential theoretical views have been put forward: a *comparator model* [Frith et al. 2000] and *retrospective inference view* [Wegner and Wheatley 1999]. The *comparator model* suggests that the comparison between predicted and actual consequences of an action through sensorimotor processes determines the sense of agency [Frith et al. 2000; Blakemore et al. 1999] (see Figure 2.5). Thus, the mismatch caused by spatial and temporal distortion of movements or outcomes can attenuate the sense of agency [Haggard and Chambon 2012]. Indeed, numerous studies have shown evidence that discrepancies between the actual movement and the corresponding visual feedback [Franck et al. 2001; Farrer, Bouchereau, et al. 2008] or sensory outcome [Blakemore et al. 1999; Sato and Yasuda 2005] of the action negatively affect the sense of agency. In comparison, *retrospective inference view* emphasizes external situational cues [Wegner and Wheatley 1999].

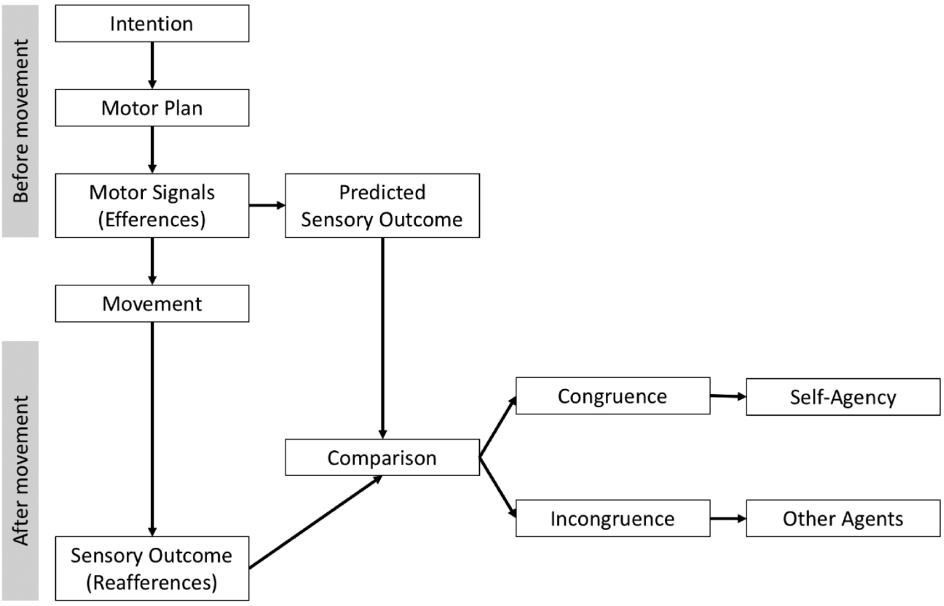


Figure 2.5 – A schematic overview of the comparator model [Zaadnoordijk et al. 2019], adapted from David et al. [2008].

According to Wegner's theory of apparent mental causation [Wegner and Wheatley 1999], the sense of agency arises if (1) an intention precedes an observed action (priority), (2) the intention is compatible with this action (consistency), and (3) the intention is the most likely cause of this action (exclusivity). Therefore, priming is often used to modulate the sense of agency by manipulating prior conscious thought about an outcome [Moore, Wegner, et al. 2009; Wenke et al. 2010; Linser and Goschke 2007]. However, the sense of agency is increasingly recognized as being based on a combination of internal motor signals and external evidence about the source of actions and effects [Moore, Wegner, et al. 2009; Wegner, Sparrow, et al. 2004; Wegner 2004]. Thus, although spatial and temporal contiguity between one's own and observed movements are the main cues for sense of agency [Haggard and Chambon 2012; Farrer, Bouchereau, et al. 2008; Franck et al. 2001], higher-level cognitive processes, such as background beliefs and contextual knowledge relating to the action, also influence the induction of sense of agency [Moore 2016; Desantis et al. 2011]. Such knowledge led to the proposition of dividing the SoA into two components: the judgment and feeling of agency. Applied to the context of avatars, these components can be defined as such: the actions performed by the avatar are judged by users, i.e. "did the avatar performed the action I wanted?", referred as the judgment of agency, but also, in a pre-motor phase, "can the avatar perform the action I want?", referred as the feeling of agency [Synofzik et al. 2008].

2.5.3 The Sense of Self-location

"The sense of self-location refers to one's spatial experience of being inside a body and it does not refer to the spatial experience of being inside a world" [Kilteni, Groten, et al. 2012]. It is therefore important to differentiate it from the sense of presence, although it has a spatial character. It is possible for instance to have a sense of presence in a VE while not being represented by an avatar, but the sense of self-location necessarily refers to either the biological, artificial or virtual body. As stated by Kilteni et al. [2012], those two concepts can nonetheless be considered as complementary in their role to constitute one's spatial representation. The sense of self-location towards one's own biological body is normally egocentric, as when we look down towards our body, we see ourselves spatially into it from our own perspective. Hence, when it comes to the sense of self-location towards a virtual body, the visual perspective (or point of view) towards the virtual body will have a strong importance towards the sense of self-location experienced [Blanke and Metzinger 2009]. For instance, it has been shown that physiological responses to threat are higher when induced towards an artificial body seen from a first person point of view rather than a third person point of view [Petkova, Khoshnevis, et al. 2011]. More recent works also showed that first person point of view towards an avatar could easily induce a sense of self-location

towards it [Gorisse, Christmann, Amato, et al. 2017]. Interestingly, the sense of self-location can also be modulated when synchronous visuo-tactile correlations are applied to a virtual limb or body [Slater, Perez-Marcos, et al. 2008]. For instance, Normand et al. [2011] showed that a sense of self-location induced with synchronous multisensory stimulation with a larger belly size could result into an altered perception of the personal space (see Figure 2.6).

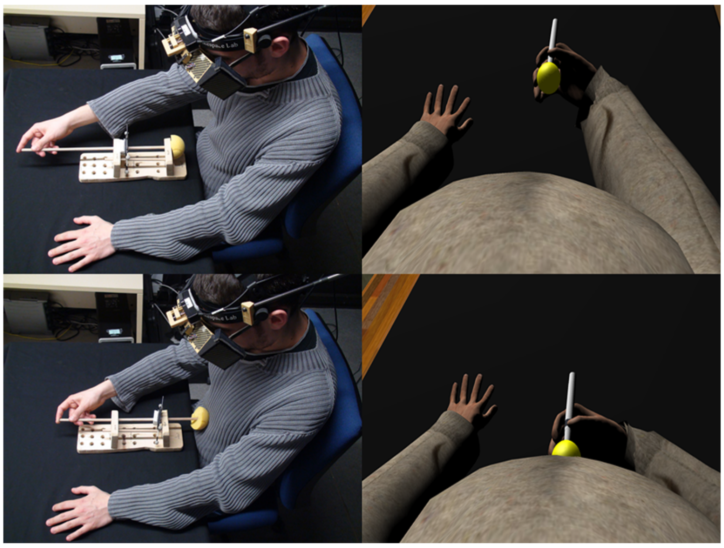


Figure 2.6 – Illustration from the study of Normand et al. [2011]. Whenever participants poke their belly with the rod, the virtual belly is touched at the same time by the virtual rod. It therefore provides synchronous multisensory stimulation towards the larger virtual body.

2.5.4 Methods of Measure of the Sense of Embodiment

Assessing users' SoE is important in order to understand how they perceive the avatar they are embodied in. A critical point therefore lies in the possible ways to measure it, associated with the known difficulty of measuring subjective feelings. In this section, we hence describe seminal works related to the methods of measures of the SoE.

2.5.4.1 Subjective Measures of the SoE

As being related to a subjective experience, the first and most common ways to assess users' SoE has been the use of subjective questionnaires. More precisely, previous studies on embodiment in VR adapted individual questionnaires from originating experiments conducted in the physical world, such as the RHI [Botvinick and Cohen 1998; Longo, Schüür, et al. 2008].

Yet, there is no validated questionnaire to this day, which reinvigorated the interest of researchers to design such standardized questionnaire. This was first emphasized by Gonzalez-Franco and Peck [2018], who identified a set of questions which they organized in six different categories: body ownership, agency and motor control, tactile sensations, location of the body, external appearance, and response to external stimuli (see Table 2.2).

However, the use of subjective questionnaires is being more and more challenged for that it depends on users' own understanding of questionnaires, which may be impacted by many internal differences between users [Jahedi and Méndez 2014; Slater 2004]. In addition, another concern in regards to subjective questionnaires was raised by Insko [2003] about the study of presence in VR, stressing out that because they are post-immersion, they do not measure potential impact of time on the subjective presence nor potential influences of events during the experiment. For this reason, other research tended to explore alternatives to assess this perception of the virtual body.

2.5.4.2 Objective Measures of the Sense of Embodiment

The first studies exploring objective measures of the SoE were conducted out of VR, within the frame of RHI studies. For instance, the observation of proprioceptive displacement of users hand towards the rubber hand was found to be correlated with an elevated sense of ownership towards the rubber hand [Longo, Schüür, et al. 2008]. This measure was at a later stage used in the context of virtual embodiment, as in the works of Sánchez-Vives et al. [2010]. In addition, behavioral changes were also shown to be exploitable as an objective measure of the SoE by Kilteni et al., who showed that people with higher SoE experienced high behavioural changes [Kilteni, Bergstrom, et al. 2013]. More precisely, they conducted a study in which participants played hand drum in VR while embodied in a virtual avatar which representation was modulated. Interestingly, in one avatar representation, participants showed significant increases in their movement patterns for drumming compared to other representations, and it was found that the stronger the stronger the sense of ownership towards the avatar was in such representation, the greater this behavioral change was. Furthermore, recent research also explored the potential of brain-measurement techniques such as surface ElectroEncephaloGraphy (EEG) as a measure of the SoE, and highlighted for instance the existence of neurophysiological markers [Jeunet et al. 2018] correlated to the sense of agency.

Nevertheless, the most common objective measure of the SoE remains to this day the physical response to a virtual threat towards the avatar. Indeed, the introduction of a threat has become a popular mean of assessing if users are well embodied in their avatar. The threats in such context

Table 2.2 – Questionnaire of Mar-Franco and Peck [2018]. Questions in italics are control questions.

Variable	Question
Ownership	1) I felt as if the virtual body I saw when I looked down was my body. 2) *It felt as if the virtual body I saw was someone else.* 3) *It seemed as if I might have more than one body.* 4) *I felt as if the virtual body I saw when looking in the mirror was my own body.* 5) *felt as if the virtual body I saw when looking at myself in the mirror was another person.*
Agency	6) It felt like I could control the virtual body as if it was my own body. 7) The movements of the virtual body were caused by my movements. 8) I felt as if the movements of the virtual body were influencing my own movements. 9) *I felt as if the virtual body was moving by itself.*
Tactile Sensations	10) It seemed as if I felt the touch of the ____ in the location where I saw the virtual body touched. 11) *It seemed as if the touch I felt was located somewhere between my physical body and the virtual body.* 12) It seemed as if the touch I felt was caused by the ____ touching the virtual body. 13) It seemed as if my body was touching the ____.
Self-Location	14) I felt as if my body was located where I saw the virtual body. 15) *I felt out of my body.* 16) I felt as if my (real) body were drifting towards the virtual body or as if the virtual body were drifting towards my (real) body.
Appearance	17) It felt as if my (real) body were turning into an “avatar” body. 18) At some point it felt as if my real body was starting to take on the posture or shape of the virtual body that I saw. 19) At some point it felt that the virtual body resembled my own (real) body, in terms of shape, skin tone or other visual features. 20) I felt like I was wearing different clothes from when I came to the laboratory.
Response to External Stimuli	21) I felt that my own body could be affected by ____. 22) I felt a ____ sensation in my body when I saw ____. 23) When ____ happened, I felt the instinct to ____. 24) I felt as if my body had ____. 25) I had the feeling that I might be harmed by the ____.

can be of many form, such as the threat of a sharp object towards the virtual body (see Figure 2.7). This practice relies on the assertion that if users react to a virtual threat towards their virtual body, they must have a strong sense of embodiment towards it. Indeed, several studies showed that the sense of ownership towards a body was connected with increased affective response to threat towards the body [Yuan and Steed 2010; Zhang and Hommel 2016].

Figure 2.7 – Two examples of threat in embodiment studies. Left: study by Argelaguet et al. [2016] where participants have to avoid different types of obstacles with their virtual arm, such as a rolling saw. Right: study by Gonzalez-Franco et al. [2014] in which a knife threatened participants' hand.

The first studies exploring the relation between body ownership and response to threat were based on the RHI. Armel et al. [2003] were among the first ones to show that response to a threat towards a rubber hand was linked to the assimilation of the rubber hand as into one's own body image. The threat response was in that case assessed by skin conductance response (SCR), e.g., if the rubber hand was "injured", participants displayed a higher skin conductance. Rapidly, the use of a threat has been extended to RHIs targeting deeper exploration of the body sense of ownership. Indeed, SCR measures after a threat introduction have been used to show that amputees of an upper-limb could feel ownership towards a rubber hand prothesis [Ehrsson, Rosén, et al. 2008] but also that it was possible to feel ownership towards two rubber hands in supplementary to the physical hand [Ehrsson 2009] or to a third rubber arm supplementary to the two physical arms [Guterstam, Petkova, et al. 2011]. Studies exploring the concept of body-swapping also used SCR as an objective measure of ownership towards another body (either a manikin or someone else's body) in a context of out-of-body experiences, using an HMD coupled to a video camera oriented down at the manikin or someone else's body [Petkova and Ehrsson 2008; Guterstam and Ehrsson 2012]. Quickly, research exploiting the use of a threat to measure the sense of ownership have been brought to virtual reality. Yuan and Steed [2010] were the first ones to transpose the RHI in Immersive Virtual Reality (IVR) and by the same time the first ones to use SCR as a measure of ownership when a threat is introduced. Ma et al. [2013] however questioned their findings in that they did not consider it succeeded in proving that SCR to threat was linked with ownership, because one can have a similar affective resonance when someone else is hurt. They [Ma and Hommel 2013] also showed in their own study that if response to a non dangerous impact was linked to the sense of ownership, response to a threat appeared to be independent of the sense of ownership, which is in contradiction with other research using SCR to threat as an objective measure of ownership [Zhang, Ma, et al. 2015; Hägni et al. 2008].

The introduction of threat in embodiment studies has thus already been widely used as an objective measure of the SoE. Yet, no research has been conducted to evaluate the actual effect of introducing a virtual threat on the subjective measures of the SoE. Indeed, while the response to a virtual threat is used as a measure of the SoE, to our knowledge, it has never been considered as a possible influencing effect. In other words, the response to a virtual threat is associated to a strong SoE towards an avatar, but it was never verified whether its introduction could actually impact an initial SoE. For this reason, a chapter of this thesis investigates this concern.

2.6 Factors Influencing the Sense of Embodiment

The study of the SoE in VR has enabled to investigate many angles of one's own body perception, taking advantage of the plasticity of a virtual avatar and all the experimental modulations it can provide. But the study of the SoE has also been clearly beneficial for the development and design of avatars for various applications. Indeed, with the recent technological developments, avatars are now highly used in VR for research purposes, e.g., for 3D graphics and games research [Trepte and Reinecke 2010], behavioral research in psycholinguistic [Heyselaar et al. 2017], or psychological research in general [Zhang and Hommel 2016]. Therefore, in order to provide efficient avatars for such applications, many research works used the study of the SoE in order to test different technical configurations of avatar. From this research emerged different "factors of influence" towards the three subcomponents of the SoE: the sense of ownership, the sense of agency and the sense of self-location. However, most of these works considered factors related to the avatar characteristics. In this thesis, we introduced a visual categorization of the factors influencing the SoE that groups together several layers of factors (see Figure 8.5). For this reason, we describe in the following illustrative works exploring the factors influencing the SoE in these three categories: VE-related, Avatar-related, and User-related factors. Because factors related to the avatar were the most studied, we will start recounting this part of the literature.

2.6.1 Avatar-Related Factors

A notable number of studies have explored the factors related to the avatar that could influence the different subcomponents of the SoE. Mainly, those factors are mapped over avatar characteristics that cover different ranges of feedback given to the user towards the avatar, such as the appearance and real-time animation of avatars. This relies for instance on the representation of the avatar (e.g. realistic vs. cartoon display) or the hardware constraints (e.g. upper-body vs. full-body tracking).

In order to ensure that users feel a high SoE towards their avatar in VR, it is necessary to understand how the combination of such characteristics are accepted by users, and affect their perception of the resulting avatars. These characteristics can be grouped under more global factors that were studied regarding their potential influence towards the subcomponents of the SoE.

2.6.1.1 Appearance

An important constraint in avatar design relies on the representation of the avatar, i.e., its appearance. Indeed, to have realistic avatars of high fidelity, 3D photogrammetry scan systems of high complexity are needed, which consequent cost and intricacy make them not always accessible. It is therefore common to have less realistic avatars in VR applications, from cartoon display to only specific body parts represented (e.g., heads, hands and feet for instance).

The appearance of the avatar can be divided into several characteristics: the general structure of the virtual body, the shape and dimension of body parts and the render style. These characteristics combined together contribute to different levels of avatar realism, anthropomorphism and fidelity towards the user's real body, which were demonstrated to be of critical influence on the elicitation of the sense of ownership towards avatars [Argelaguet et al. 2016; Lin and Jörg 2016]. For instance, Lin and Jörg [2016] showed that this sense was stronger with a more realistic human hand model compared to a non-anthropomorphic hand model (see Figure 2.9). Similarly, while it is still possible to feel ownership towards full-body avatars with different degrees of anthropomorphism [Lugrin, Latt, et al. 2015], the Sense of Ownership tends to be higher when the avatar clothes and skin tone match the user's ones [Maselli and Slater 2013]. In a higher level of customization, the use of 3D scanned replicas has been also considered [Waltemate, Gall, et al. 2018; Gorisse, Christmann, Houzangbe, et al. 2019], and results have shown that they positively influence the sense of ownership. However, such approaches require complex 3D capture setups, which are costly but also require consequent additional time in order to scan participants. In addition, the road to highly realistic avatars also leads to a risk of uncanny valley. It was suggested by Mori [2012] that increasing human likeness, an entity becomes more and more accepted by humans, until a point where the entity evokes negative feelings or even disgusts. It can occur in VR by embodying for instance a woman in a very masculine avatar although highly realistic: the important realism of the avatar will make more obvious the physical differences with the woman's appearance, which will deteriore the experience (see Figure 2.8). It is therefore important to try to avoid this point when designing realistic avatars. Schwind et al. [2018] provided to that aim helpful guidelines in order to avoid such uncanny valley effect, such as for instance the avoidance of "dead eyes" and therefore the use of eye tracking to animate eyes gaze..

Figure 2.8 – "Female participant not immersed using male hands due to a perceived mismatch between VR hair and musculature and her appearance in real life" [Schwind, Wolf, et al. 2018]

Furthermore, if the latest research mainly focused on exploring avatars with high realism and fidelity, other research also explored the capability of users to feel ownership towards an avatar which differs from their self-representation in terms of body structure [Laha et al. 2016] or gender [Slater, Spanlang, Sanchez-Vives, et al. 2010], showing that it is in general possible to elicit a Sense of Ownership towards such avatars. For instance, Laha et al. [2016] showed that it is possible to feel ownership towards a third arm, while Slater et al. [2010] showed that body transfer illusion between male subjects and virtual avatar female body could elicit a Sense of Ownership. In addition, another study [Banakou, Groten, et al. 2013] showed that adults could feel a sense of ownership while embodied in a child-like body. Interestingly in this study, the appearance of the avatar seemed to impact users mind as when embodied in a child-like body, participants tended to overestimate object sizes and experienced change in their attitude. Similar phenomenon was also observed in the experience of Banakou et al. [2018], in which participants embodied Einstein and experienced significant improvement in cognitive task performance. However, such effect was not observed in every study. For instance, Verhulst et al.[2018] conducted an experiment in which participants (of a normal BMI on average) were embodied in a normal or an obese virtual body and were asked to buy and evaluate food products in the immersive virtual store. While authors expected to trigger stereotype reactions and therefore observe changes in participants behaviour and shopping patterns, there were no significant differences between the groups. One possible explaination argued by the author is that possibilty an obese virtual body would require some other non-visual stimulus, e.g., the sensation of the extra weight or the change in body size.

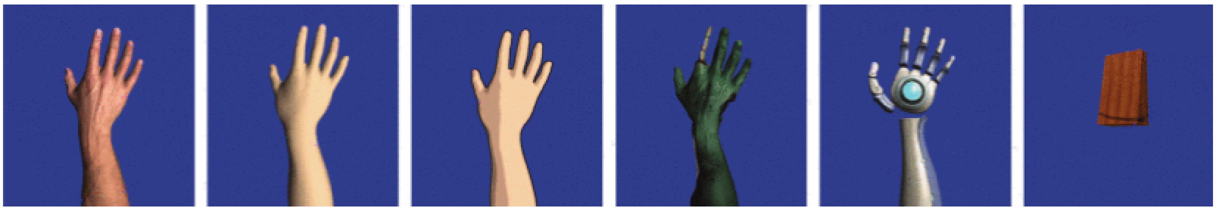


Figure 2.9 – Different degrees of realism and anthropomorphism of virtual hands representations [Lin and Jörg 2016].

2.6.1.2 Control

To animate the avatar in real time according to the users' movements with as much precision as possible, advanced tracking solutions are necessary, such as full body suits with inertial sensors (e.g. Xsens system [Roetenberg et al. 2009] (see Figure 2.10, left)) or infrared tracking systems (e.g., Optitrack) (see Figure 2.10, right)). Lower quality alternative solutions are also possible, depending as well on the control necessity (either one limb of the avatar or full body avatar). For instance, for the control of one arm of the avatar, the use of an infrared sensor such as Leap Motion as used in the study of Argelaguet et al. [2016] is comfortable has it provides forearm and finger tracking without the need to wear gloves or markers. When only the upper-body of the avatar needs to be controlled, the use of inverse kinematics is also often used [Huang, Fratarcangeli, et al. 2017; Luciano and Banerjee 2000], as it only requires one controller for each hand in addition of the HMD in order to compute an estimation of the avatar position and orientation. The addition of other trackers is also easy in order to adapt the inverse kinematics solution to the whole body or to make it more precise. More recently, an intense focus has been set on a higher level of detail in the control of the avatar, such as fingers animation and real-time 3D facial control. However, this last element is really challenging because of the large occlusion caused by the HMD [Song et al. 2018]. Interestingly, sometimes no control at all is provided, and only animations are played on the avatar, on which users do not have any effect. For instance, Gonzalez-Franco et al. [2020] found that self-identification was increased towards an avatar on which facial animations were pre-baked and based on facial idle expressions.

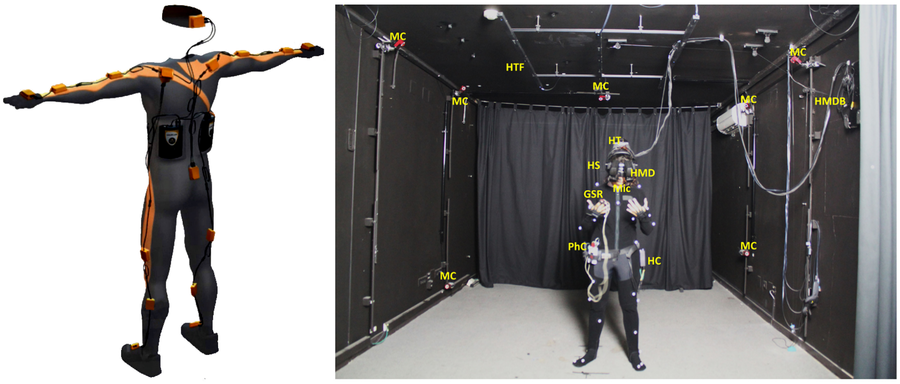


Figure 2.10 – Left: “Xsens MVN consists of 17 inertial and magnetic sensor modules. Data is transmitted by a wireless connection to the laptop computer on which the processing is performed and visualized. A suit is used for quick and convenient placement of sensors and cables” [Roetenberg et al. 2009]. Right: Hardware elements of the embodiment system from [Spanlang, Normand, Borland, et al. 2014], the participant wears a suit with retro-reflective markers for full body motion capture, which are then tracked using 12 Optitrack motion capture cameras.

Overall, the control of an avatar has a strong influence on the SoE, and more precisely it has a direct impact on users’ sense of agency. Indeed visuomotor congruence between real and virtual body movements highly contributes to the Sense of agency [Caspar et al. 2015], while discrepancies between visual and motor information tend to decrease it [Farrer, Bouchereau, et al. 2008; Sanchez-Vives, Spanlang, et al. 2010]. Regarding the feeling of agency, other studies showed that it is possible for users to feel an illusory Sense of agency towards actions they did not cause when some requirements are respected, such as a close match between users intentions and subsequent actions [M Wegner et al. 2004; Kokkinara, Kilteni, et al. 2016]. Nagamine et al. [2016] also support the important role of motor control in the recognition of one’s own actions. Regarding avatar animation techniques, such as the use of inverse kinematics or motion capture, some studies explored the influence of motion artifacts (latency, noise) in such techniques on the Sense of agency, showing for instance that it impacts the Sense of agency but does not break it [Waltemate, Senna, et al. 2016]. More precisely, Waltemate et al. [2016] found that the sense of agency and body ownership only decline at a latency higher than 125 ms, and deteriorate for a latency greater than 300 ms. Others also explored the impact of such controls on the Sense of Ownership [Roth, Lugrin, Büser, et al. 2016] or on the Sense of Embodiment [Parger et al. 2018].

However, no studies explored to our knowledge the influence of the actual animation technique on the Sense of agency.

2.6.1.3 Point of View

In the field of non-immersive 3D video games that involve an avatar, there exist multiple ways to depict users' point of view towards their avatar [Taylor et al. 2002]: first person Point of View (PoV), and different types of third person PoV (top down over the shoulders of the avatar, facing the avatar, "god view" overhead pull-out, etc.). Studies in the area agree in that the third person PoV in this context may increase the awareness of the virtual space surrounding the avatar while acting through the avatar with the game environment [Taylor et al. 2002]. Yet, they also agree on that it is an advantage in detriment of users' immersion [Denisova and Cairns 2015].

In the field of VR, the third person PoV had been encouraged for its help in adjusting the posture of an avatar, and to compensate the effect of distance compression usually perceived by participants in immersive systems [Boulic et al. 2008; Covaci et al. 2014]. However, the third person PoV is not the natural perspective we have towards our body, which is why some research tackled the question of this type of PoV regarding the sense of embodiment towards an avatar [Debarba et al. 2015]. Indeed, the PoV of users in the virtual environment with respect to their avatar determines the spatial relationship between their avatar and their virtual body. Such relationship can have an impact on where one perceives oneself to be located and thus alters the Sense of Self-Location. For example, a first-person PoV can easily induce the Sense of Self-Location [Gorisse, Christmann, Amato, et al. 2017], while a third-person PoV is more likely to reduce it [Maselli and Slater 2014; Galvan Debarba et al. 2017]. However, in out-of-body experiments, the illusion of self-Location might persist if it is preceded by a stimulation period [Bourdin et al. 2017]. More precisely, the presence of congruent visuotactile stimulation was also shown to be a key factor regarding the Sense of Self-Location, as it may lead users to mislocalize themselves towards the virtual body, to a position outside their bodily borders [Lenggenhager et al. 2007]. Interestingly, Debarba et al. [2015] proposed in their study an alternative method that enabled participants to switch between first and third PoV. They showed that subjective evaluations of embodiment were similar in such condition of "alternation" between first and third PoV compared to a basic first PoV. In particular, they argued that such a method could be valuable in the context of VR applications for Post Traumatic Stress Disorder or phobia therapy. They justify this potential application for that the first person PoV could allow participants to experience a strong SoE towards their avatar, while switching the PoV to third PoV in case of a threat could help them modulate the intensity of the therapy in a reassuring manner.

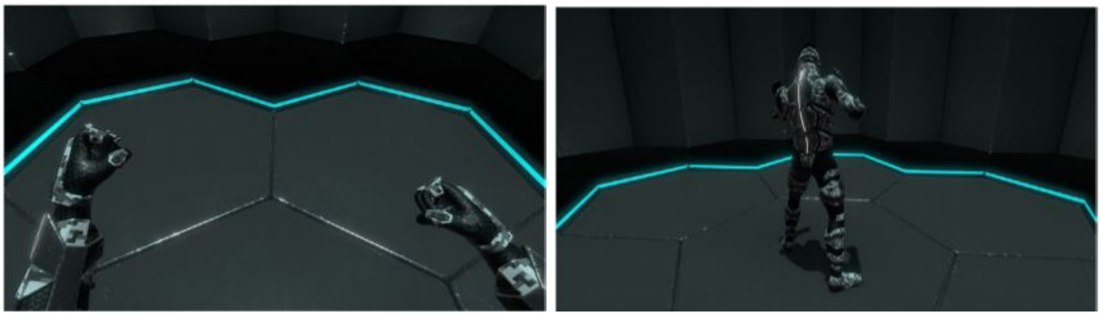


Figure 2.11 – Illustration of two different point of views in virtual reality explored by Gorisse et al. [Gorisse, Christmann, Amato, et al. 2017].

2.6.1.4 Haptic Feedback

Some research also investigated the potential impact of haptic feedback on the SoE. The role of haptic feedback is to provide the physical component of an interaction, from basic to more complex interactions [Bergamasco and Ruffaldi 2011]. Several elements were identified as contributors of the overall haptic feedback [Lederman and Klatzky 2009]:

- **Proprioceptive feedback**: information about the position of our body parts and their movements.
- **Kinesthetic feedback**: information about the forces applied to the body.
- **Tactile feedback**: information covering the touch with surfaces.
- **Vestibular feedback**: perception of the gravity vector.

The first link between haptics and the SoE was therefore introduced through the study of the RHI, as it was showed that synchronous visual and tactile stimuli could elicit the illusion of the ownership of a fake limb (rubber hand) [Botvinick and Cohen 1998]. Such effect was also replicated in VR, towards a virtual arm, by Slater et al. [2008]. However, these studies have in common that they involve the participation of an experimenter, that will physically make a action towards the participants to provide tactile feedback. Other research works explored therefore the potential of wearable haptic systems in the context of virtual embodiment, such as the work of Spanlang et al. [2010] which describes a system that generates touch on the real person's body when the avatar is touched by the mean of a haptic vest mounted with vibrators. Furthermore, Fröhner et al. [2018] explored two types of haptics feedback (vibro-tactile and kinesthetic feedback), and showed that haptic feedback significantly improves the subjective embodiment of a virtual hand and that force feedback leads to stronger sense of ownership. In addition, a more recent work from Krogmeier et al. [2019] found a positive correlation between the SoE and a form of vibro-tactile feedback. In this study, participants were immersed in a VE in which virtual characters were walking past them and sometimes walked too close and bumped into them. In that case, a vibro-tactile feedback was either provided with different degree of coherence (strength, synchronicity) or not at all. The results indicated that the SoE of participants was significantly higher with any kind of vibro-tactile feedback compared to no vibro-tactile feedback at all. In addition, vibro-tactile feedback with high intensity or non synchronicity elicited lower SoE, which the authors argue might suggest that the SoE could be partially linked to the logical interactions of the environment (e.g., a lower SoE for interactions that are not coherent or plausible). While plausibility of the VE was considered by Slater et al. as a component that contributes to the realistic response that users may have towards the VEs, its impact on the SoE remains neglected to this day. Moreover, while not fully related to virtual embodiment, the use of wearable haptic systems has been particularly exploited in research in VR social interactions [Huisman et al. 2014; Goedschalk et al. 2018], in which haptic feedback is used to convey a sense of "social touch".

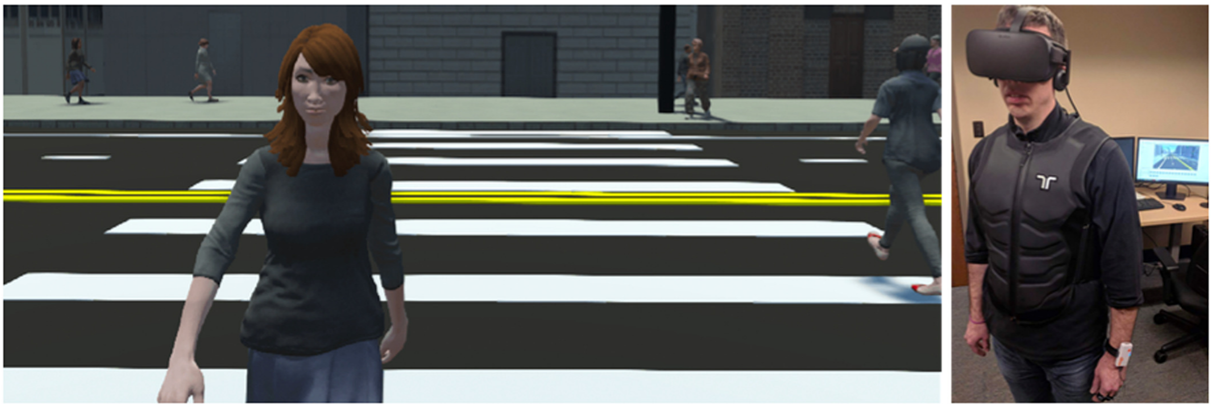


Figure 2.12 – Example of visuo-tactile feedback used in an embodiment study. [Krogmeier et al. 2019]

2.6.1.5 Auditory Feedback

A core of research also explored the potential impact of auditory feedback on the way we perceive our virtual body [Tajadura-Jiménez, Banakou, et al. 2017]. Interesting works explored the relation between sound and body perception on the physical body (without VR). For instance, it was shown that auditory distance of action sounds could influence perceived tactile distances on one's arm [Tajadura-Jiménez, Väljamäe, et al. 2012]. This result suggests that the auditory feedback of an action can recalibrate the mental representation of one's own arm length. In that line, additional research explored the impact of smell combined with sound on the body perception, and found that scent stimuli had an impact of participants own weight perception and enhance the effect of sound of the perceived body lightness [Brianza et al. 2019]. While those last works were not conducted in VR, they open up a wide range of questions regarding the potential influence of auditory feedback on the way we perceive avatars, and reinvigorate the interest in exploring the influence of auditory cues on the SoE.

2.6.1.6 Inter-relation Between the Factors Influencing the Sense of Embodiment

In the previously presented research, some factors appeared to be clearly linked to a specific subcomponent of the SoE. However, other research showed that their influence is more complex, and that some interrelations may exist within the factors and the subcomponents they influence. For this reason it is also interesting to have knowledge for each factor of its influence on all the subcomponents of the SoE.

A number of studies have shown that one isolated factor can impact more than one subcomponent. For example, while the appearance factor seems to be mainly connected to the sense of ownership, it could increase the control expectations over the virtual body. In the work of Argelaguet et al. [2016] for instance, a virtual hand with lower realism elicited a stronger sense of agency over a realistic virtual hand. Authors hypothesized that the decrease in the sense of agency was due to the mismatch between the control mechanism and the actual appearance of the virtual hand. Users' expectancy about the actual interactions capabilities of a realistic virtual hand were not met, decreasing their sense of agency. On the same basis, while the control factor seems directly linked to the sense of agency, Steptoe et al. showed that the sense of ownership towards an extra body part (virtual human tail) was higher when users could actually control it by moving their hips [Steptoe et al. 2013]. Thus, suggesting that the mere fact of being able to control your virtual body has an effect on the sense of ownership. Similarly, the work of González Franco et al. [2010a] showed that being able to control the upper-body of the avatar elicited a higher sense of ownership that when just an animation was played. It was also shown by Kokkinara and Slater. [2014] that multisensory congruence such as visuo-motor-tactile congruence enhances the sense of ownership, and that it can preserve the same sense of ownership between third-person and first-person PoV towards an avatar [Galvan Debarba et al. 2017], even though in most cases the sense of ownership is higher in first-person PoV [Gorisse, Christmann, Amato, et al. 2017].

This highlights that the point of view factor is not only related to the Sense of Self-Location but that it can also influence the Sense of Ownership.

However, due to all possible inter-connections between the factors influencing the sense of embodiment and its subcomponents, it remains challenging to quantify their impact on the perceived Sense of Embodiment as a whole. An analogous question was raised by Kilteni et al. [2012] regarding the relationship between the SoE and its subcomponents. Some research for instance would place the Self-Location as the most important subcomponent [Blanke and Metzinger 2009] while others would suggest the sense of ownership to be of low significance [Preester and Tsakiris 2009] and the Sense of agency to be of much importance [Tsakiris, Prabhu, et al. 2006]. Overall, Kilteni et al. [2012] insisted on the lack of current knowledge regarding the weight of each subcomponent contribution to the SoE, which coincides with the gap of knowledge regarding the importance of each factor regarding their influence on the SoE as an entire complex entity and not towards its specific subcomponents.

Studies exploring the influence of factors towards the SoE therefore usually focus on one factor at a time and measure its influence on the SoE. However, such measures do not allow the assessment of inter-relations between the factors influencing the SoE. Indeed, the assessment of this kind of inter-relations is challenging in terms of experimental protocol due to the numerous amount of possible factor combinations. To this respect, an axis of this thesis aims at better understanding the inter-relations among these three factors.

2.6.2 Factors related to the Virtual Environment

As depicted in section 2.2, the VE characteristics have a strong impact on users' experience of VR, mainly impacting their sense of presence. However, the potential influence of factors related to the VE on the SoE remains weackly explored. In this thesis, we were interested in one aspect of the VE that we believed could influence users' SoE: the fact of sharing VEs with other users. Indeed, when being immersed in a VE with other users, the avatar takes much more sense as it does not only convey users personal spatial representation, but it also enables them to situate other users in the VE. In the following, we therefore depict several works about avatars in the context of shared virtual environments.

2.6.2.1 Avatars in Shared Virtual Environments

As people commonly interact and collaborate with each other in real life, the need to enable such collaborations to create more immersive VR is nowadays increasing. Historically, such questions paved the way to the development of Collaborative Virtual Environments (CVEs) [Sharma and Chen 2014] as for instance social VR developed by Facebook (see Figure 2.13), telepresence platforms, and led to several types of experiments, e.g., regarding social interaction and group behavioral studies [Slater and Steed 2002]. For instance, multi-user immersion was used to evaluate whether users in a small group would be more efficient in realizing a task in the real world or in virtual reality [Slater, Sadagic, et al. 2000], with results suggesting that the immersed person tended to emerge as the leader in virtual groups, but not in real meetings. To evaluate and enhance the quality of such shared experiences, the concept of Presence was originally explored.

Figure 2.13 – Avatars from Facebook Social VR

2.6.2.2 Influence of Avatars on Presence in Shared Virtual Environments

In the context of multi-user experiences, it was demonstrated that seeing other users in the VE could be taken as an evidence of one's proper existence in the VE, and could increase the sense of presence [Heeter 1992]. This supported the necessity to differentiate new notions, such as co-presence and social presence, from personal presence [Slater, McCarthy, et al. 1998].

- **Social Presence** was defined in 1976 by Short et al. [1976] as *"the degree of salience of the other person in the interaction and the consequent salience of the interpersonal relationships"*. According to them, social presence is a factor of great influence on the quality of communication in mediated communication contexts. It can also be more generally defined as a measure of the perceived presence of another person [Heidicker et al. 2017]. The term is also sometimes replaced by the word "co-presence" although they do not refer exactly to the same thing. Biocca et. al [2001] provided in that sense a more detailed definition of social presence, dividing into three dimensions: psychological involvement, behavioral engagement and co-presence.

— **Co-presence** refers to the sense of being together with a focus more oriented on the psychological experience [Nowak 2001]. It is indeed the main difference between social presence and co-presence, where one refers respectively to the communication medium and how it is perceived by users and the other relates more to the psychological interaction between users [Nowak 2001; Schroeder 2002].

Those terms became highly employed when conducting studies on CVEs, for example in [Poeschl and Doering 2015]. It is indeed quite interesting to wonder how being with others in the same VE might influence the way we perceive it. It was for instance showed by Slater et al. [1999], that co-presence in VR has for consequence to amplify users' reactions, making a "bad" situation worse and a "good" situation better. Following these results, several studies naturally focused on the effects of the user representation on the sense of presence in shared VEs. In particular, they demonstrated that embodying users in anthropomorphic and realistic avatars also increases their own sense of presence [Nowak and Biocca 2003], and more generally enhances their whole VR experience [Bailenson et al. 2006; Roth, Waldow, et al. 2017]. For instance, it was demonstrated that changing the avatar representation had a direct effect on the quality of social interactions in shared VEs, and more precisely that social interactions tend to be impeded by non-realistic avatars [Roth, Lugrin, Galakhov, et al. 2016].

However, while measuring the quality of VR shared experiences with multi-user immersion has clearly required to explore new concepts related to the sense of presence, such as co-presence and social-presence, the sense of embodiment which is widely studied for single-user experiences is seldom explored in this context (see Figure 2.14 for a summarized representation of these concepts). For this reason, one axis of this thesis has been to explore the influence of sharing a VR experience on the sense of embodiment.

2.6.2.3 Shared Body Experiences

Another interesting aspect of shared VR experiences has been to investigate the possibilities of shared body experiences. Some previous studies, although not always using VR, have developed shared body experiences, e.g., two individuals sharing 1PP [Petkova and Ehrsson 2008; Kasahara et al. 2016], kinesthetic experiences [Nishida and Suzuki 2017], or body representations [Petkova and Ehrsson 2008; Mazzurega et al. 2011; Tsakiris 2008; Sforza et al. 2010; Mazzurega et al. 2011; Tajadura-Jiménez, Grehl, et al. 2012]. In particular, Petkova and Ehrsson. [2008] introduced the perceptual illusion of body swapping and showed that 1PP of another person's

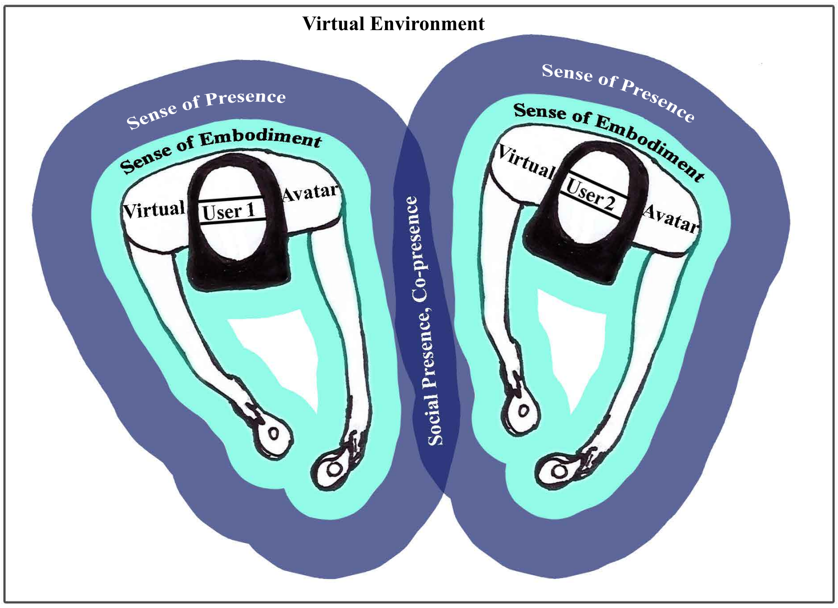


Figure 2.14 – Representation of two users immersed in the same VE, and experiencing respective subjective senses of embodiment (towards their own avatar), presence (towards the VE they share) and social/co-presence (towards their experience of being with one another in the VE).

body, in combination with the receipt of correlated multisensory information from the body, was sufficient for inducing body ownership (see Figure 2.15). Mutual paralleled first-person-view-sharing systems, in which a person can observe others' first-person video perspectives as well as their own perspective in realtime, are also used in entertainment, remote collaboration, and skill transmission systems [Kasahara et al. 2016; Kawasaki et al. 2010; Poelman et al. 2012]. Other approaches have also explored the sharing of other senses, e.g., BioSync [Nishida and Suzuki 2017] which is an interpersonal kinesthetic communication system allowing users to sense and combine muscle contraction and joint rigidity bidirectionally through electromyogram measurement and electrical muscle stimulation. Lastly, the enfacement phenomenon is a self-other merging experience, in which participants reported that morphed images of themselves and their partner contained more self than other only after synchronous multisensory stimulation on their faces [Mazzurega et al. 2011; Tsakiris 2008; Sforza et al. 2010]. Through the evidence of a field of exploration of shared body experiences in VR and the potential impact of such experiences on the SoE, another axis of this thesis has been to explore the impact of shared body experiences on the SoE.

Figure 2.15 – Experiment of body swap illusion conducted by Petkova and Ehrsson [2008], in which participants experienced the illusion that the experimenter's arm was their own arm and could sense their entire body just behind this arm.

2.6.3 User-Related Factors

The two previous sections have addressed questions related to "external" factors related to the avatar and the virtual environment, that are likely to influence users' Sense of Embodiment, while painting a review of the related topics. In this section, we raise questions regarding the impact of internal factors (related to the user) on the SoE. Indeed, while most studies are able to show general trends of the influence of such "external" factors, the inter-user variability remains non-negligible. In practice, we can observe that some people easily believe in the illusion of virtual embodiment, while others are in the contrary totally refractory. This section reports a number of works which have explored the role of inter-personal differences (e.g. personality) in VR. Because of the amount of work that was done in the past on the influence of inter-personal differences on presence, we first look at this specific aspect of the related work.

2.6.3.1 Role of Individual Differences in Presence

Several works investigated the link between the sense of presence and individual differences, in which models with different dimensions, like the OCEAN model, have been used in order to characterise inter-personal differences. The OCEAN model, also known as the "Big Five" personality traits, is a taxonomy of personality traits that uses common language descriptors in order to identify five personality dimensions: Openness to experience, Conscientiousness, Extraversion, Agreeableness and Neuroticism [Rothmann and Coetzer 2003]. For example, it was found that agreeableness was positively associated with spatial presence [Sacau et al. 2005]. Weibel et al. [2010] studied the link between the Big Five traits and immersive tendency (which contributes to the sense of presence [Ling et al. 2013]) and found that openness, extraversion and neuroticism were positively correlated with immersive tendency. However, a number of studies have found contradictory results. For example, regarding the influence of extraversion, it was found to be positively [Laarni et al. 2004] or to be negatively correlated [Jurnet et al. 2005] with presence.

In addition to the "Big Five", other personality traits that have been investigated are absorption (the disposition for having episodes of "total" attention that fully engage one's representational resources [Tellegen and Atkinson 1974]) and dissociation (the lack of normal integration of thoughts, feelings, and experiences into the stream of consciousness and memory [M. Bernstein and W. Putnam 1987]). They were first both found associated with reality judgment [Baños, Botella, García-Palacios, et al. 1999]. Then their influence on presence was studied and they were sometimes both found positively correlated with presence [Sacau et al. 2005], sometimes only dissociation was associated with presence [Murray et al. 2007] or neither of them was correlated [Phillips et al. 2012]. Kober and Neuper [2013] also found that absorption was a good predictor of presence, no matter what presence questionnaire was used. Moreover, empathy is another trait which has been studied in the past, and demonstrated to be related to feeling a higher sense of presence [Nicovich et al. 2005; Sas and O'Hare 2003; Ling et al. 2013].

Finally, the Locus of Control (LoC) was also studied regarding its potential influence on the sense of presence. It has been often used in the fields of education, health, and clinical psychology. It refers to the degree to which people believe that they have control over the outcome of events in their lives, as opposed to external forces beyond their control [Levenson 1981]. The Internal-Personal-Chance (IPC) test [Hanna 1974] is one of the measurements for LoC, indicating a person's relative standing on each of the three dimensions of internal, powerful others, and chance. Among them, the individuals with a strong internal LoC believe events in their life are derived primarily from their own actions. Some research demonstrated that the locus of control had an influence on the sense of presence. However contradictory results were found, namely that either an external [Murray et al. 2007] or internal [Wallach et al. 2010] locus of control was improving presence depending on the study.

2.6.3.2 Individual Differences and Embodiment

The majority of the works addressing such internal factors on the SoE have mainly focused on the RHI in the physical world. The influence of body awareness, a cognitive ability that makes us aware of our body processes, has been studied but no correlation was found with the strength of RHI [David, Fiori, et al. 2014]. Regarding personality and RHI, it has been found that the RHI is stronger for empathic people [Asai et al. 2011; Seiryte and Rusconi 2015]. The sense of ownership in the RHI was also found to be correlated with traits like the Novelty Seeking trait (from the TCI-R questionnaire) or Psychoticism (from the SCL-90-R questionnaire) [Kállai et al. 2015]. Also, higher responses to the RHI have been reported for people suffering from personality or psychotic disorders: dissociative subtype of post-traumatic stress disorder (PTSD) [Rabellino et al. 2016], schizophrenia [Peled et al. 2000; Thakkar et al. 2011] and schizotypal personality disorder [Asai et al. 2011; Van Doorn et al. 2018]. Finally, recent works have started to focus on the potential role of personality traits on virtual embodiment. One example being the work of Jeunet et al. [2018] which showed that the feeling of agency is linked to an internal locus of control.

The literature review thus showed both a clear interest and important results regarding the influence of personality on user's sense of presence in VR and on users' SoE in the physical world. Some more recent work also revealed an influence of the locus of control, a personality trait, on the SoE in VR. This last result highlighted the potential role of individual differences in the elicitation of the SoE in VR and in this way, raised the concern of exploring deeper their possible link to the SoE in VR. For this reason, an axis of this thesis has been to explore the influence of a wider range of individual differences on the SoE in VR.

2.7 Conclusion

In this chapter, we described several concepts related to avatars in virtual reality. After introducing the concept of VEs and notions of perception of VEs, we reported illustrative studies about own-body perception in the physical world, and in VR, setting up the ground for the further presented research works. Afterwards, we introduced the concept that is the most relied on in the context of studies focusing on avatar: the Sense of Embodiment, and we depicted several works studying its three subcomponents: the sense of ownership, the sense of agency and the sense of self-location. After showing that these three subcomponents could be modulated by many means (e.g.,visuomotor and visuotactile feedback) and could be measured in different ways (subjective vs objective measures), we re-used our three-layer-factor representation (see Figure 8.5) to articulate several studies on the factors influencing the SoE: Avatar-related, VE-related and User-related factors. We first focused on the layer that contains the most factors studied: Avatar-related factors, and depicted seminal studies on factors that we identified as being the most studied regarding their impact on the SoE: the appearance, control, point of view, presence of haptic and auditory feedback. Second, we broadcasted works studying the avatars in the context of shared virtual environments, highlighting that if the sense of presence had widely been studed in shared VEs involving avatars, the SoE in such context was on the other hand weackly investigated. Third and finally, we depicted illustrative works related to the potential influence of user's individual differences on the SoE. We showed in particular that if several studies had investigated the relation between users' personality traits and the sense of presence, the link to the SoE in VR remained unclear. Overall, what can be extracted from these works is that despite the consequent core of research exploring the SoE in VR and how it can be affected by several factors, we believe that there still remains a dark area of potential factors not related to the avatar that might influence the SoE and therefore the appreciation of avatars in VR, more precisely, factors related to the user and the VE. This thesis hence aims at filling the gaps within these points of concern, in several contributions presented in the following chapters.

PART I

Influence of the Virtual Environment on the Sense of Embodiment

"Some heades haue taken two headis better then one: / But ten heads without wit, I wene as good none."
"Two heads are better than one."

John Heywood, 1546 (old english)

3

Studying the Sense of Embodiment in Shared Virtual Reality Experiences

Abstract:

This chapter aims at studying the influence of sharing a VE with another user on the SoE. It presents a study in which pairs of users were immersed simultaneously in the same VE while being embodied in their own proper avatar. There were asked to perform a task together, that consisted in a whac-a-mole game, with several degrees of competitiveness. Users also experienced the task alone, and in front of a mirror, and subjective as well as objective mesures of the SoE were collected for each condition. In the following, we describe the protocol of the experiment, as well as results that we further discuss.

3.1 Introduction

In this first part of the thesis, we are interested in factors related to the VE that are likely to influence the SoE of users towards their avatar. A very popular aspect of VEs that is still currently increasing, is that VEs can be shared and experienced with other users. This capacity reinvigorated

Figure 3.1 – Setup of the experiment: each user was able to interact in the virtual environment with his own avatar, while the physical setup provided both a reference frame and passive haptic feedback. From left to right: experimental conditions Alone, Mirror and Shared; Physical setup of the experiment.

the interest in developing efficient shared VE such as Collaborative Virtual Environments (CVEs) [Sharma and Chen 2014] or telepresence platforms, that would allow users to collaborate, work or play together in VR. In addition, such platforms have been the playground of an increasing number of studies and types of experiments, e.g., regarding social interaction and group behavioral studies [Slater and Steed 2002]. In such context, it is particularly relevant to represent users with an avatar in the VE, in order to spatially situate them towards other users. As mentioned in Chapter 2, the impact of avatars on shared VR has been initially assessed by studying their influence on the sense of presence, which showed overall a strong influence of avatars and their appearance on the whole VR experience (increasing the sense of presence, impacting social interactions, etc. [Roth, Lugrin, Galakhov, et al. 2016; Nowak and Biocca 2003]). However, the SoE which is widely studied for single-user experiences is seldom explored in this context. For this reason, this chapter presents our contribution to explore the influence of sharing a VR experience on the sense of embodiment. For this aim, we conducted an experiment where ten pairs of participants sat in front of a table, with co-localized physical and virtual setups. They were embodied in a co-localized avatar (see Figure 3.1) and were asked to perform a gamified task. Each participant performed the experiment both alone and facing another embodied user. In order to assess users' SoE, we collected subjective questionnaires during and after the experiment, as well as physical reactions to the presence of a visual threat introduced in the form of sharp spikes at the edges of the table in half of the experimental conditions.

3.2 Experiment

We hypothesized that being immersed in the same VE while sharing a common task together with another user will reinforce the SoE. In particular we made the assumption that seeing another user's avatar will reinforce the user experience, and that it will enable users to experience a higher sense of ownership and agency. In order to test this hypothesis, we designed an experiment in which users could perform a specific task, i.e. a whac-a-mole game (see Figure 3.1), alone or together with another user. To ensure that potential differences would not only be due to additional visual cues due to the presence of another body, we also introduced a condition where users were immersed alone in front of a mirror and therefore saw their own reflection. In order to assess users' SoE, we collected subjective questionnaires during and after the experiment. We also introduced a visual threat in half of the trials, in the form of sharp spikes at the edges of the table, and measured users' behavioral changes while performing the task.

3.2.1 Participants

Twenty male unpaid participants from the university campus took part in the experiment (age: min=21, max=33, and avg=26±2), recruited both among general students and staff. They were all naive with respect to the purpose of the experiment, had normal or corrected-to-normal vision, and gave written and informed consent. The study conformed to the declaration of Helsinki. Participants took part in the experiment in pairs. Among the participants, 9 subjects had none to very limited previous experience with VR, 6 had some previous experience, and 5 were familiar with VR. All participants were right-handed male Caucasians, to match the visual appearance of the virtual avatar as much as possible. In order to avoid any gender interaction bias, we always used same-gender avatars for each participant pair, with the assumption that mixing genders in pairs could have influenced interaction between users.

3.2.2 Technical Details

We developed a collaborative platform in Unity in which two users could share the same virtual and real environment, and interact in real time. Our setup was based on two HTC Vive Head-Mounted Displays (HMDs) with four HTC Vive controllers, to immerse participants in the VE. Users were embodied in anthropomorphic virtual avatars in 1PPOV (see Figure 3.4 left). In the center of the tracking zone, two chairs and a table were placed. A thin foam layer covered the table to avoid impacts of the HTC Vive controllers. The physical furniture had its virtual counterpart in the VE providing both a reference frame and passive haptic feedback (see Figure 3.1). Finally, the experiment took place inside a standard virtual office.

In order to elicit high levels of embodiment, we chose to use realistic human avatars in our experiment. Because sharing experiences with other embodied users means that people do not

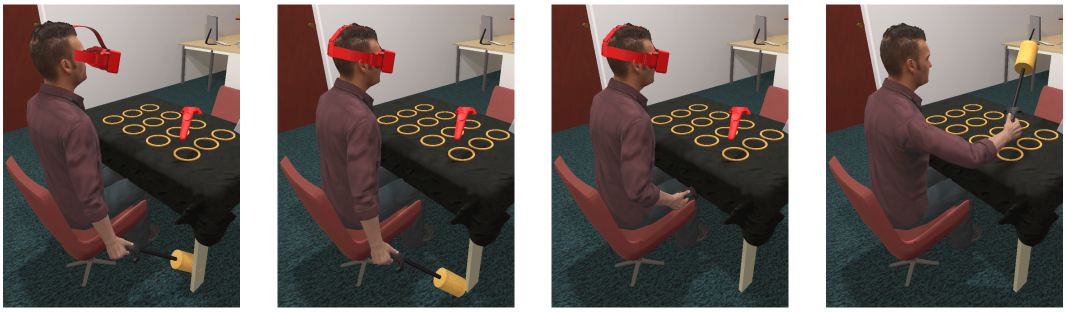


Figure 3.2 – Main steps of the Inverse Kinematics based avatar animation. The physical position and orientation of the Vive HMD and controllers are displayed in red, and used as targets for our IK method. Steps are in order: 1) avatar initial resting pose, 2) rotation of the torso to align the avatar's head with the HMD, 3) elbow flexion to satisfy the distance between the shoulder joint and the target wrist (inferred from the controller transformation), and 4) final pose after rotating the shoulder to align the wrist with the target wrist.

only observe their own virtual body, but also others', a lot of attention was given to the animation quality of the avatars, i.e. on the way avatars moved according to their user's movements. In particular, animation and control quality are strongly linked to the sense of agency, and are therefore extremely important to measure the SoE. We then detail two main aspects of the animation of the avatars: 1) the calibration of the avatar size to the user's and 2) the animation of the avatar according to the user controls (i.e. HTC Vive head and hands tracking).

3.2.2.1 Avatar Calibration

In order to provide the best experience, it is important to match the participants' height with their avatar's, in particular to ensure that the camera viewpoint is located near the head of the avatar, and at a correct height from the floor. Before starting the experiment, participants were therefore asked to sit upright on their chair while wearing the HMD and to place their hands on the table while holding the controllers. Then, the avatar's torso was automatically scaled to align the vertical position of the HMD with the avatar's eye height.

3.2.2.2 Avatar Animation

Avatars were controlled by user movements through the use of the HTC Vive HMD (head) and controllers (hands). However, as users were sitting in a chair, we only needed to animate the upper part of the avatar body, which was performed using a two-step process. First, we used the HMD position to drive the torso of the avatar by rotating the torso (from spine to head) around the pelvis (Figure 3.2.2), thus ensuring the alignment of the HMD position with the avatar's eyes (i.e. leaning based on the user's movements). Yet, during pilot studies we noticed that such alignment was not sufficient when users looked behind them, which often occurs when users want to explore a new virtual environment. As shoulders were not tracked, only the head of the avatar turned in such cases, which created visual skinning artifacts around the neck. As real life people would actually twist their spine to look behind them, we therefore included an additional linear combination of the head rotation along the spine which minimized skinning artifacts.

As a second step, the arms of the avatar were then driven with a standard analytical Inverse Kinematics method using the position and orientation of the Vive controllers. The rig of the character hands were modified ensuring that the character grasped the controller as naturally as possible. As the character rig and the current position and orientation of the controllers were known, the position and orientation of the characters' wrist could be inferred (hereafter referred as target wrist). At that stage we make two assumptions: first that the predefined relative transformation locating the Vive controller in the hand coordinate system is the same for all subjects and second, that it remains constant during the experiment, i.e. subjects do not modify their initial controller grasping posture. This approach provided satisfying results.

Moreover, characters were manually posed at rest (before animation) with the arms at a 10° abduction angle from the vertical of the trunk (see Figure 3.2.1). During run-time, forearms were first flexed so that the distance between wrist and shoulder joints matched the distance between the shoulder joint and the target wrist (Figure 3.2.3). Then, we computed the normal vector to the plane defined by the shoulder, wrist and target wrist positions, and rotated the arm around this vector to align the wrist with the target wrist (Figure 3.2.4). This method allows us to avoid elbow singularities, while creating arm poses driven by the original abduction angle of the avatar at rest. While the elbow location might not match the users', this is a solution commonly used in interactive applications [Kulpa et al. 2005; Hecker et al. 2008]. It is also important to point out that the avatars' static hand postures matched a natural grasping of the virtual HTC controllers.

3.2.3 Experimental Protocol

Upon their arrival, participants read and signed the experiment consent form and filled in a demographic questionnaire. Then, they were briefed about the experiment and immersed into the VE (occupying one of the two chairs). As some experimental conditions (see Section 3.2.4) required one user and others two users, we scheduled the experiment so that 1) the first user performed all single-user conditions, then 2) the second user arrived and the two-users conditions were performed, and finally 3) the first user left and the second user performed the single-user conditions (see Figure 3.3).

Before each condition participants performed a short training session, in which they were

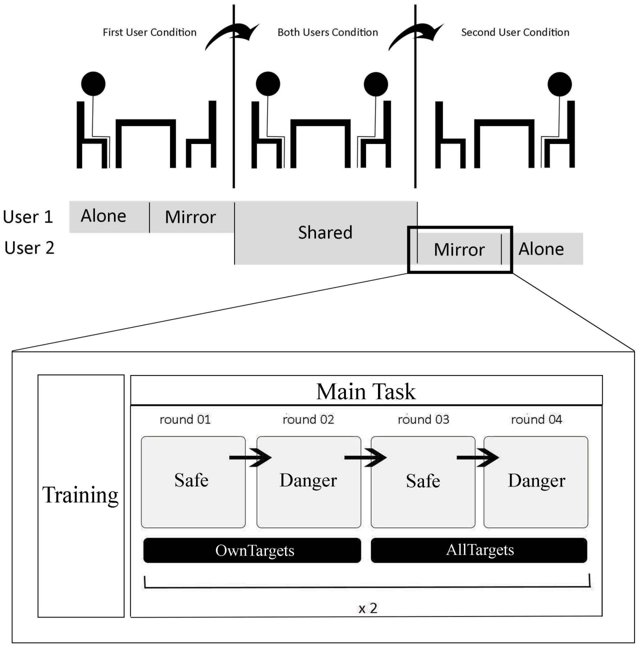


Figure 3.3 – (Top) Experiment organization for each pair of users, according to the three conditions: Alone, Mirror, Shared. Alone or Mirror conditions were randomly presented first. (Bottom) Details of each condition organization: training followed by the main task, where OwnTargets or AllTargets were presented in random order. Danger and Safe stages were also presented in random order.

asked to grasp virtual cubes and to place them at specified locations to become familiar with the system and the environment (see Figure 3.4 center). Using the original 3D model of the HTC Vive controller, we attached a 3D claw model on top, which was animated when pressing the trigger button of the controller. The virtual claw was used to pick up the cubes and to move them. When two users shared the same environment, they performed this task together by positioning successively one cube at a time.

After the training, participants performed the main task which consisted in a whac-a-mole game. A virtual foam hammer was attached to the virtual HTC Vive controller of the user's dominant hand, which participants used to hit the moles. Moles appeared at random time intervals and at random spots on the table (4x3 spots), and stayed visible from 0.8 to 2.6 seconds. They were also color-coded to indicate to participants which moles they had to hit (see Section 3.2.4). A score panel displayed the accumulated score for each round. Hitting the right mole increased the score by one, and hitting a wrong mole decreased the score by one. The task was moderately demanding in terms of attention and required fast reaction. Furthermore, while the non-dominant was not actively used in the task, users were still holding a controller tracking their non-dominant hand location. This information was used both for analysis of embodiment and animation purposes. Finally, participants filled in a subjective questionnaire at the end of each block of the experiment in order to gather subjective impressions on presence and embodiment.

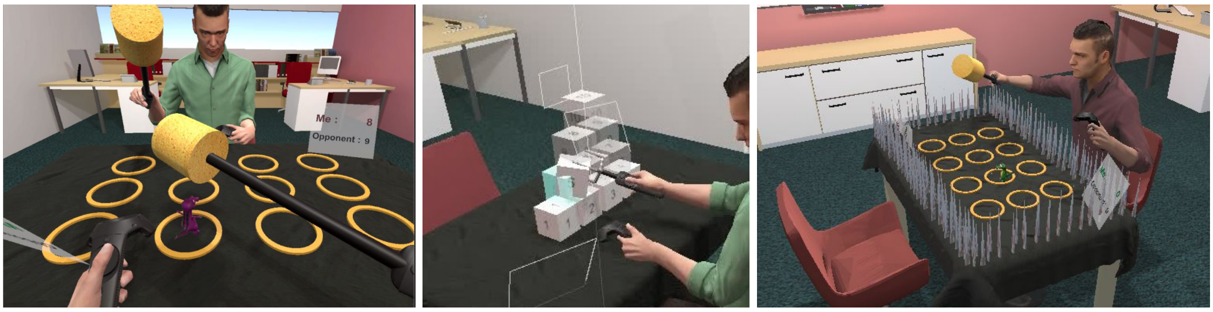


Figure 3.4 – 1PPOV when performing the whac-a-mole task (left), 3PPOV when performing the Training (center) and Danger: virtual spikes appeared around the virtual table in order to threaten the virtual body (right).

3.2.4 Experimental Design

In our within-subject design, three independent variables were considered: Experience, Target and Danger. The main independent variable (Experience) considered whether there was a shared experience or not, and had three levels (Figure 3.1): 1) the user performed the task alone (*Alone*), 2) two users performed the task at the same time, sitting in front of each other (*Shared*), and 3) a control condition in which the user performed the task alone, but a mirror in front of him enabled to see his avatar (*Mirror*). The second independent variable (Target) was the difficulty of the whac-a-mole task, which had two levels: 1) users could hit all the moles (*AllTargets*) and 2) users could hit only half of the moles (*OwnTargets*). In *OwnTargets*, users were asked to hit only the moles corresponding to their color (matching the color of their shirt, green or purple), and hitting the wrong mole decreased their score. In *AllTargets*, all moles had the same color (white). This variable allowed to create two different situations. One more competitive, where users had to compete for the same moles, and another less competitive, where they only focused on their moles. Finally, the addition of potentially harmful elements in VEs is commonly used in embodiment studies to assess behavioral responses [Hoyet et al. 2016; Zhang and Hommel 2016]. Thus, we considered the additional independent variable (Danger) whether there was a potential threat to the virtual avatar (*Danger*) or not (*Safe*). The potential threat were 25cm-height sharp spikes placed around the table (Figure 3.4, right).

The overall organization of the experiment is summarized in Figure 3.3, and further described below. The experiment was divided into 3 blocks, corresponding to the three Experience conditions. The Experience conditions were not fully-counterbalanced due to practical reasons, as single conditions were always done together. Yet, half of the users did the shared condition first and half did it last. The Alone and Mirror conditions were counterbalanced for each pair of users. Each block included the training task and eight rounds of the whac-a-mole task (2 Target x

2 Danger x 2 repetitions). Each round had a duration of 1 minute and the when a threat was induced it always appeared 3 seconds after the beginning of the round and remained present until the end of the round. Target and Danger levels were fully counterbalanced. There were 32 moles for each round. At the end of each block, users removed the HMD and filled a subjective questionnaire to gather their subjective impressions. In total the experiment lasted approximately one hour.

The measured data (dependent variables) took into account performance and behavioral measurements which might show changes on the sense of embodiment. Regarding performance, we only measured the mean *selection time*. It considered the time required to hit the mole after its appearance (in seconds). For each user, only trials in which they successfully hit a mole were considered. We did not consider the user score because performance was close to 100% in most conditions. Regarding behavioural measures, we mainly focused on the mean elevation of the dominant and non-dominant hands (in meters), which could be influenced by the virtual threat. Finally, there is also the subjective responses for the final questionnaire (see Table 3.1). The questionnaire was inspired from previous work [Botvinick and Cohen 1998; Longo, Schüür, et al. 2008; Kalckert and Ehrsson 2014] and divided into three groups: presence, ownership and agency. For each question, participants were asked to rate their answer on a 7-point Likert scale. Participants also reported general comments and feedback at the end of each questionnaire.

In summary, considering our experimental design, our main hypotheses were:

H1 The more competitive the task is, the lower the mean selection time will be.

H2 The mean elevation of the dominant hand will be higher when the Danger is visible.

H3 The mean elevation of the non-dominant hand will be higher when the Danger is visible.

H4 Presence ratings will be higher when sharing the VE.

H5 Body ownership ratings will be higher when sharing the VE.

H6 Agency ratings will be higher when sharing the VE.

Table 3.1 – Questionnaire used in the experiment.

Variable	Question
Presence	- Please rate your sense of being in the virtual office space, on the following scale from 1 to 7, where 7 represents your normal experience of being in a place. I had a sense of “being there” in the virtual office space - To what extent were there times during the experience when the virtual office space was the reality for you? There were times during the experience when the office space was the reality for me... - When you think back about your experience, do you think of the office space more as images that you saw, or more as somewhere that you visited? The office space seems to me to be more like ... - When you think back about your experience, do you think more as being elsewhere, or more as being in the office space? I thought more as... - Consider your memory of being in the office space. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By ‘structure of the memory’ consider things like the extent to which you have a visual memory of the office space, whether that memory is in colour, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements. I think of the office space as a place in a way similar to other places that I’ve been today... - During the time of the experience, did you often think to yourself that you were actually in the office space? During the experience I often thought that I was really seated in the office space...
Ownership	- I felt that the virtual body was my own body. - I felt that the virtual arms were part of my body. - I felt that the virtual arms could be harmed. - I felt that my real arms could be harmed. - I felt that virtual arms were not part of my body. - I felt as if the virtual arms were from someone else’s body.
Agency	- I felt as if the virtual body moved just like I wanted it to, as if it was obeying my will. - I expected the virtual body to react in the same way as my own body. - I felt like I controlled the virtual body as if it was my own body.

3.2.5 Results

Three-way Repeated Measures ANOVA analyses were performed to test the significance of the Experience, Danger and Target levels for each dependent variable. When main or interaction effects were found ($p < 0.05$), they were explored using pairwise Tukey post-hoc tests. Only significant results are discussed. Anderson-Darling normality tests were performed to ensure a normal distribution of the data. Effect size was computed using partial eta squared (η_p^2).

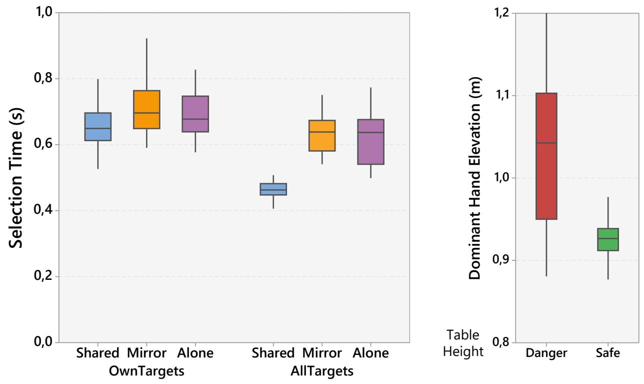


Figure 3.5 – Results summary. (Left) Boxplot of the selection time grouped by Target and Experience. (Right) Boxplot of the dominant hand elevation when hitting the mole grouped by Danger.

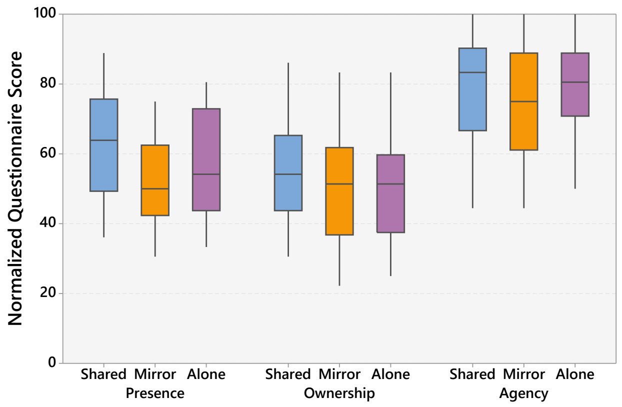


Figure 3.6 – Boxplot of questionnaire ratings for presence, ownership and agency, grouped by Experience.

Selection Time: The ANOVA analysis showed three main effects regarding Experience ($F_{2,32} = 47.31$, $p < 0.001$, $\eta_p^2 = 0.75$), Danger ($F_{1,16} = 22.08$, $p < 0.001$, $\eta_p^2 = 0.58$) and Target ($F_{1,16} = 232.46$, $p < 0.001$, $\eta_p^2 = 0.94$), Figure 3.5 (Left) shows the summary of the results. Post-hoc tests showed that participants were significantly faster in the Shared condition compared to the Alone or the Mirror conditions. They were also significantly faster in AllTargets compared to OwnTargets, as well as in the Safe compared to Danger stages. Furthermore a two-way interaction was found between Experience and Target ($F_{2,32} = 35.75$, $p < 0.001$, $\eta_p^2 = 0.69$), where post-hoc tests showed that users were the fastest in the Shared × AllTargets combination. The interaction effect supports **H1**, as the most competitive condition Shared × AllTargets had the lowest selection time. **H1** is further supported by the main effects of Experience and Target.

Dominant Hand Elevation: The ANOVA analysis only showed a main effect of Danger ($F_{1,16} = 33.18$, $p < 0.001$, $\eta_p^2 = 0.67$).

Post-hoc tests showed that users placed their dominant hand higher when the danger was visible than when it was not ($M = 1.03m$; $SD = 0.08m$ vs $M = 0.93m$; $SD = 0.04m$; table height: 0.8m; see Figure 3.5, Right). This result supports **H2** and showed an adaptation of users' behaviour due to the appearance of the virtual spikes.

Non-Dominant Hand Elevation: The ANOVA analysis showed a main effect of Experience ($F_{2,32} = 11.03$, $p < 0.05$, $\eta_p^2 = 0.19$) and a two-way interaction effect between Target and Danger ($F_{1,16} = 10.61$, $p < 0.01$, $\eta_p^2 = 0.4$). However, post-hoc tests did not show any significant effect, and mean differences were not higher than a few centimeters overall. The mean elevation was $M = 0.81m$; $SD = 0.05m$ which shows that it remained very close to the height of the table (0.8m). In summary, this result does not support **H3**.

Questionnaires: Data from the questionnaires was structured into three groups (presence, ownership and agency). For each group and user, the scores were added (control questions were included by inverting their score), and normalized between 1 and 100 to improve readability (see Figure 3.6). In order to enable the analysis of the interaction effects (mixed ANOVA analysis) due to the non-continuous nature of the data, unaligned rank transform [Wobbrock et al. 2011] was applied. The ANOVA analysis considered the within-subjects variable Experience and the between-subjects variable Order (Shared first vs Shared last). Regarding presence, the ANOVA showed a main effect of Experience ($F_{2,32}$=8.56, $p < 0.001$). Post-hoc tests showed that the overall sense of presence was higher for the Shared condition compared to the Mirror condition ($p < 0.05$) and also for the Alone condition ($p < 0.05$). This result supports **H4**. Regarding ownership, an interaction was found between Experience and Order ($F_{2,32}$=5.35, $p < 0.01$), which was not confirmed by the post-hoc analysis. Still, a deeper analysis seems to suggest that participants who started with the Shared condition gave a lower ownership score for the Alone and Mirror conditions compared to the users finishing with the Shared condition. Yet, the results are inconclusive and do not support **H5**. Finally, for agency the ANOVA showed a significant main effect of Experience ($F_{2,32}$=3.63, $p < 0.05$). Post-hoc tests showed that agency ratings were lower for the Mirror condition compared to the Shared condition ($p < 0.05$). This result does not support **H6**.

3.3 Discussion

The main objective of the experiment was to evaluate the influence of sharing a VE with another user also embodied in an avatar on each other's SoE. In this Section we discuss how the results can be interpreted in terms of body ownership and agency but also provide additional insights regarding user engagement and presence. We further illustrate those results with written user feedback, either supporting our results analysis or highlighting other aspects that did not arise from the variables observed during the experiment.

3.3.1 User Performance and Engagement

The results on selection time show that users were significantly more "efficient" in performing the task when sharing the VE and in particular in the competitive level (AllTargets). First, the main effect of Target shows that participants required less time to select the targets in the AllTargets level vs the OwnTargets level. This result can be explained by the increased cognitive load for the OwnTargets level as users had to determine whether the target had to be selected or not. Second, the main effect of Experience could be explained by an increased user engagement during the competitive (Shared) condition, leading to decreased selection times. In particular, this effect was stronger in the AllTargets level (significant interaction effect). This explanation is supported by Lalmas et al. [2014] who stated that user engagement depends on time, and that challenge is an element that influences engagement.

Moreover, it is important to highlight that when users had to compete for the same moles, the evaluated selection time is actually the best out of two participants, rather than their individual performance. Despite the fact that selection time was significant lower in the Shared condition compared to the other conditions, it is still possible that this observation could have influenced this result. However, our result is also supported by the other subset of trials where users had to hit their own moles, in which a relevant change in the selection time was also observed depending on Experience, a result also supported by the increased presence ratings in the Shared condition.

User feedback was also in line with this interpretation. Users expressed a positive feeling towards the fact of sharing the VE with another user: *"This is more enjoyable and realistic with a partner"*, *"The feeling of incarnating the avatar is globally better with a second user in front"*, or *"It is better with another person during the experiment"*.

Finally, users were also faster when the danger was not displayed. While it is difficult to separate selection time from the fact that their dominant hand was closer to the table in the Safe stage, or from the fact that they might have been more careful in the Danger stage, it is nonetheless important to take into consideration that users displayed different "motor strategies".

3.3.2 Body Ownership

First of all, subjective results on body ownership did not show any significant differences at the level of Experience. On average, participants reported a medium level of body ownership $M = 52.0$; $SD = 15.7$. Yet, participants starting with the Shared condition demonstrated a tendency to report lower ownership ratings for the Alone and Mirror conditions. This suggests that the Shared condition might have provided an upper bound sense of ownership depending on whether users started with the Shared condition or not. Nevertheless additional experiments would be required to validate this assumption.

Regarding the behavioural measurements, we found that participants placed their dominant hand higher in the presence of a virtual threat. Several hypotheses may explain this phenomenon: is this reaction due to the fact that they feared the threat? Or is it just because they avoided the collision? As it is established that a response to a threat testifies of a high sense of ownership, we make the assumption that participants were really punctually afraid for their virtual body to be harmed. On the contrary, it appeared that participants nearly did not raise their non-dominant hand when the threat was introduced, independently of the condition tested. It is however unclear why participants would react to a threat with their dominant-hand and not with their non-dominant hand. As participants did not need to interact using their non-dominant hand, it is therefore possible that this absence of interaction could be a reason why participants seemed to less appropriate their non-dominant virtual hand as their own. It is also possible that the non-dominant hand was less present in the field of view of participants, which could have influenced their reaction. In either way, participants were never asked to maintain their non-dominant hand on the table. This observation opens the question whether body ownership is uniform regarding the entire virtual body, or depends on whether a body part is active or not.

In addition, comments from users also testified of a reaction toward the virtual threat: *"I felt strange when I moved my arm through the spikes"* or *"When the table was surrounded with spikes, it took me several seconds to be at ease with them and to realize I could not be harmed"*. These remarks support the results of the dominant-hand height regarding the sense of ownership towards the virtual body. It has been considered the possibility that participants would actually move their hand thinking that touching the spikes would decrease their score, as the game was quite competitive, but the way most participants quickly reacted, surprised by the danger appearing, testifies of a basic instinct to a threat toward their body.

It is also interesting to acknowledge that we did not observe a significant increase in ownership in the mirror condition, which is contradictory to previous work where the presence of such a mirror is often use to enhance the sense of ownership [González-Franco, Pérez-Marcos, et al.

2010b]. One possible explanation is that the mirror might have been distracting for participants, and have possibly highlighted small animation artifacts, which was however not reported by any participant. Furthermore, this result can also be explained due to the uncanny valley effect [McDonnell et al. 2012]. The choice of a realistic anthropomorphic avatars might have influenced how participants accepted the avatar as their virtual representation, which could be further explored in future experiments.

3.3.3 Agency

Overall the agency score was high ($M = 78.09$; $SD = 15.24$), which shows that the avatar control was realistic and efficient. We took great care in providing a high quality to the visual rendering of the virtual scene, both in terms of appearance and avatar animation. Users were immersed in a realistic environment, similar to a real office, and embodied in realistic anthropomorphic avatars.

Interestingly, the analysis of Agency scores showed that the levels of agency were lower for the Mirror condition. Indeed, three participants communicated a negative feeling towards the presence of a mirror in the VE: *"It is better without the mirror"*, *"The mirror effect creates a loss of the sense of presence, I couldn't say why, but it installs a discomfort"*, and *"I felt more immersed without the mirror"*. The possibility to look to one's own avatar motions in the mirror could have increased the chances to detect imperfections of the avatar control scheme. Also, the fact that we used inverse kinematics to animate the upper body of the avatar might have induced a lack of accuracy at the origin of those results.

Unlike the sense of ownership, to our knowledge the sense of agency had not yet been studied in relation to the presence or not of a mirror in virtual reality. For instance, while Slater et al. [2010] explored the influence on agency of synchronous or asynchronous mirror reflections in IVR, they did not compare it to a control case without a mirror. Yet their results appeared to be in conflict with previous studies that suggested the importance of motor cues for the sense of self [Jeannerod 2003]. While our results suggest differences in the agency scores between the mirror and single conditions, such differences were small, showing the need to ensure accurate avatar control to maximize the sense of agency.

3.3.4 Limitations and Future Works

One of our verified hypotheses was that competition has an impact on user performance, showing an increase in user engagement. Indeed, the wack-a-mole task had a clear competitive dimension, which had for consequence that users were more attentive and efficient. However, the increase in engagement could have reduced the awareness of participants about their virtual body. Thus, it would be interesting to consider other tasks, reducing the ambiguity between engagement and embodiment. For instance, relevant tasks could involve higher awareness of one's virtual body and of others, such as users collaborating to achieve common goals while finely controlling their virtual body.

In addition, the interaction capabilities of the task were satisfying constrained. For example, a participant reported that remaining seated, without being able to explore the room, reduced the ability of considering the virtual office as an actual real room. Further studies could explore increasing the interaction capabilities by providing the possibility to walk/navigate, or to interact with a wider range of virtual objects. Our results are also limited by the fact that we used only male participants, and further studies could be conducted using cross-gender or female participants. Finally, another aspect that requires additional research is the fact that we chose to have users sharing both the same virtual and physical environment. This implied that users eventually saw each other physically and could potentially talk and hear each other directly, which could have introduced additional implications in terms of social interactions. Our study could also be extended by involving more than two users.

3.4 Conclusion

In this chapter, we explored how sharing a virtual environment with another user could generate changes in the behaviour and the perception of the virtual experience such as influencing the sense of embodiment. Our results show that shared experiences increased user engagement and the sense of presence, which is supported by performance and subjective measurements. In addition, all experimental conditions generated a strong sense of embodiment. Taken together, our results lead the way for VR applications designers to identify the important features to consider in order to develop multi-user VE. It can now be taken as an established fact that if users are immersed embodied in respective avatars, their SoE remains quite high, and so does the quality of their experience. It is also well-known that VR finds a large public in the entertainment area, and that multi-user games are quite popular in the gaming community. It is therefore relevant in this area to consider the influence of the competitive dimension existing in these applications on users' quality of experience.

In the following chapter, we dig in the question of shared VR one step further, involving this time the sharing of the avatar it self, meaning: two users being embodied in the same avatar.

"As a body everyone is single, as a soul never."

Hermann Hesse, Steppenwolf

4

Exploring the Influence of Sharing an Avatar with Another on the Sense of Embodiment

Abstract:

This chapter aims at exploring the influence of shared VE on the SoE on a very specific angle: We are interested not only in the context of two users sharing the same VE, but in two users being embodied in the same avatar. More precisely, because sharing the same avatar rises questions regarding how users will manage to control the same virtual body and interact with the VE, we are particularly interested in how sharing the control of the avatar could influence users' Sense of Agency (SoA) towards it. This chapter therefore presents the experiment that was conducted in order to explore that matter.

4.1 Introduction

In this chapter, we introduce a new concept, termed "virtual co-embodiment." While the concept of "co-embodiment" has been recently defined outside of the scope of VR [Luria et al. 2019], this is the first study to the best of our knowledge to define "virtual co-embodiment" as a

Figure 4.1 – Our “Virtual Co-Embodiment” experience enables a pair of users to be embodied simultaneously in the same virtual avatar (Left). The positions and orientations of the two users are applied to the virtual body of the avatar based on a weighted average, e.g., “User A” with 25% control and “User B” with 75% control over the virtual body (Right).

situation that enables a user and another entity (e.g., another user, robot, or autonomous agent) to be embodied in the same virtual avatar. Such a situation raises the question about how sharing a virtual body influences ones’ perception and actions in the VE. Potential applications of this new concept range from VR-based motion training to collaborative teleoperation, e.g., to efficiently transfer physical skills from an expert to a novice, or to enable the simultaneous control of a robot by two experts as if the robot was their actual body. In such scenarios, it is therefore important to maintain the feeling of control for both users so that they have the impression that they are controlling the avatar in the same manner that they would control their own bodies. As a first step, this study focused on two users sharing the same virtual body. As seen in Chapter 2, the SoE is a theoretical framework widely used to evaluate how users perceive and accept their avatar to be their own representation in the virtual world [Kilteni, Maselli, et al. 2015; Longo, Schüür, et al. 2008]. This framework is often divided into three dimensions [Kilteni, Groten, et al. 2012]: the sense of agency (SoA), sense of self-location (SoSL), and sense of body ownership (SoBO). However, owing to the particularity of the virtual co-embodiment experience, in which users share control over their virtual body, and the potential implications that sharing this control would increase the interaction capabilities of users in a VE, we decided to focus our efforts on the assessment of the SoA. The ability to modulate the sharing of avatar control enables the possibility to assess the SoA when two users collaborate to achieve a task while embodied in the same virtual avatar. Previous research explored the influence of perceptual and motor mismatches over the SoA. Such studies showed that it is possible for users to feel agency toward actions they did not perform [Wegner, Sparrow, et al. 2004], and highlighted interesting insights regarding the SoA with its possible modulations, inspiring the following question: To which level can users experience a SoA over a shared virtual avatar?

To answer this question, we conducted a VR experiment in which 12 pairs of individuals participated. Each pair was embodied in the same shared avatar from a first-person perspective (1PP) and was asked to perform different tasks in the VE while sharing the avatar control. The control was shared by averaging the position and orientation of the hands of both users according to a predefined level of control for each user (from no-control to full-control) and by animating the avatar accordingly. Our two main hypotheses were as follows: (1) the SoA would be positively correlated with the degree of control over the shared avatar; and (2) the SoA would be positively influenced by how much the task is potentially restricting the participant's choices. In addition, as seen in Chapter 2, in a study including manipulations of the SoA in VR, based on the principles of priority, exclusivity, and consistency, Jeunet et al. [2018] suggested that the internal dimension of the Locus of Control (LoC), a personality trait, is positively correlated with participants' level of agency. We therefore assessed participants' LoC in our study, and expected to find a correlation with their SoA towards the shared avatar.

4.2 Related Work on Illusory Sense of Agency

In Chapter 2, we reviewed several works regarding shared VE, as well as shared bodily experiences. We also reviewed the theory and measures of the SoA, from which we found that spatial displacement or temporal delay between action and outcome attenuates the SoA [Haggard and Chambon 2012; Farrer, Bouchereau, et al. 2008; Franck et al. 2001]. However, we feel illusory SoA over distorted movements as long as the displacement or delay is under the threshold. For example, a recent study using VR showed that spatial manipulations of 22° of angular offset from 1PP did not attenuate SoA [Kokkinara, Slater, and López-Moliner 2015]; this showed much lower detection thresholds than previous studies without VR [Farrer, Bouchereau, et al. 2008; Franck et al. 2001]. Moreover, a study by Galvan Debarbaba et al. [Galvan Debarba et al. 2018] showed that subjects did not detect easily avatar's movement discrepancies when the nature of the distortion was not made explicit, and that subjects were biased to self-attributing distorted movements that made the task perfomed easier. In addition, illusory SoA can occur over the actions or outcomes made by someone else when there is a close match between prior intentions and subsequent actions. In a classic study by Nielsen [1963], participants were instructed to draw a straight line to the goal point. After some repetitions, the experimenter secretly inserted a mirror so that the participants were looking at another person's hand in a mirror. They experienced the illusory SoA and attributed the hand to their own. In Wegner and Wheatley's "I-spy" experiment [1999], participants and an experimenter jointly controlled a cursor. Auditory priming of action-relevant thoughts induced illusory SoA even through the

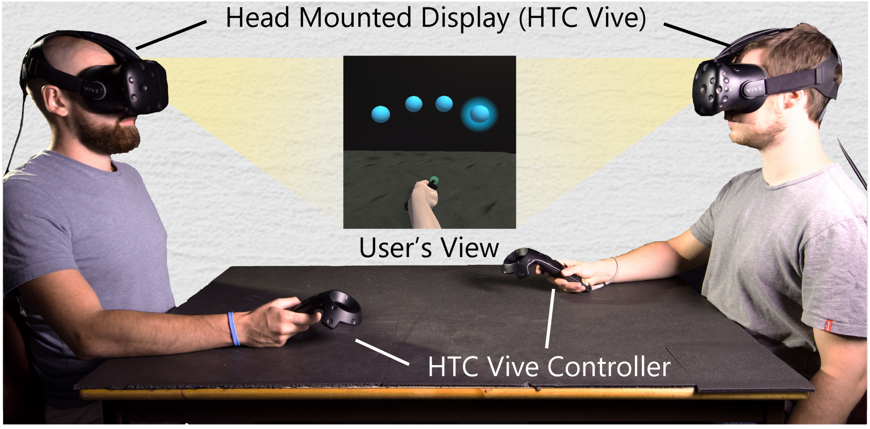


Figure 4.2 – Physical setup: two users are physically sitting in front of each other and are immersed in the same avatar from a 1PP.

cursor was being controlled by someone else. This suggests that post-hoc judgments of SoA can easily be distorted in a joint action when the action source is ambiguous. Yokosaka et al. [2014] reported that when participants watched their own and another person's hand motion alternately from 1PP, they felt illusory SoA over the movement, although they were aware that they were not performing a united motion.

Moreover, illusory SoA is possible over body movements even when no actual corresponding action is being performed. In the "helping hands" experiment by Wegner et al. [2004], participants watched themselves in a mirror while an experimenter standing directly behind them extended and moved his or her arms as if the participants themselves moved their arms. They reported that participants felt an illusory SoA for another person's hands when they were primed about instructions for that person's movements in advance, although they factually did not move. VR is also used to induce illusory SoA when passively observing movements of a walking avatar from 1PP [Kokkinara, Kilteni, et al. 2016]. To summarize, in situations where individuals do not move, the action priming and movement observation from 1PP are considered to be important for illusory SoA. Therefore, we believe that users might experience all the three aforementioned types of illusory SoA in a virtual co-embodiment experience, as the feedback component originates partially from one's own movements and partially from someone else's movements.

4.3 Co-embodiment platform

In this section, we discuss about the proposed virtual co-embodiment platform, which was used to conduct the experiment, to be described in Section 4.4.

The platform was developed in Unity and allows two users to share the same virtual environment and interact in real time, while being embodied in the same avatar. Our setup is based on two HTC Vive head-mounted displays (HMDs) with two HTC Vive controllers to immerse participants in the VE. The application runs on Unity 2018.1.0f2 at a constant frame rate of 90 Hz. Both computers are physically connected on the same network to minimize latency. Users are embodied in an anthropomorphic virtual avatar from a 1PP (see Figure 4.2). In the center of the tracking zone, two chairs and a table are placed, enabling users to sit in front of each other. The physical furniture has its virtual counterpart in the VE providing both a reference frame and passive haptic feedback. The VE in which users are immersed comprises an empty room.

In terms of avatar appearance, we chose to use a realistic model in our experiment as well as immerse users in a 1PP, as these criteria were reported by recent studies to be important for enhancing the overall SoE [Maselli and Slater 2013]. As animation and control quality are known to be strongly linked to the SoA, we primarily focused on avatar animation. This was especially challenging in our case owing to the shared control of the avatar. Note that, the differentiation of avatar animation and control inputs is necessary for its computation.

In the case of a single-user situation, the animation of the avatar depends solely on the control inputs of this user. However, in this study, the control inputs result from the combination of the inputs of two users. We therefore implemented a method that allowed the sharing of the avatar control with another user. As a virtual view that does not correspond to the user's own head movement could cause motion sickness, each user observed his/her own perspective in accordance with his/her head movement; the head position and orientation of the HMDs were not shared. Regarding the controller, we computed the weighted average of the real-time position and orientation of each user's controller, and applied it to the shared avatar's controller. The weight defining the level of control could be continuously changed from 0% to 100%. The weighted average position and orientation were then computed by interpolating between user controller positions and orientations.

Further, we chose to focus on the animation of the arms and torso because, as stated in [Jeunet et al. 2018], the arms and hands are the main body medium for interactions in VEs. In addition, in our setup, as users were seated on a chair, only animation for the upper body was required, which was animated through inverse kinematics using the Final IK Unity package. The Final

IK computed inverse kinematics using position and rotation inputs of the head and controllers of the shared avatar, obtained through the previous shared control computation. Users could thus observe the same shared avatar, the movements of which, computed by inverse kinematics, would follow more or less their own hand according to their level of control at a certain time.

4.4 Experiment

4.4.1 Experiment Summary

We conducted an experiment, in which we explored the influence of the degree of control of an avatar shared with another person on one's own SoA. More precisely, we address the two following questions. Does the degree of shared control have an impact on one's Feeling of Control (FoC) toward the avatar? Does the predictability of the avatar movement have an impact on one's FoC toward the avatar?

In the literature, the SoA was shown to largely depend on the degree of discrepancy between the predicted sensory feedback of an action and the actual outcome [Sato and Yasuda 2005]. In addition, participants were observed to feel illusory SoA over distorted movements when the discrepancy is under a certain threshold [Kokkinara, Slater, and López-Moliner 2015]. Moreover, other studies focused on situations in which participants did not move and experienced illusory SoA toward movements they did not perform, when they had prior knowledge of the action and were immersed in a 1PP [Wegner, Sparrow, et al. 2004]. Based on these findings, we hypothesized that the level of control over the avatar shared between the two participants would influence the SoA. We also hypothesized that the freedom of movement in the task and whether both participants had the same prior knowledge of the action would also influence the SoA.

To test these hypotheses, we designed an experiment in which two participants were immersed simultaneously in a VE and were embodied in the same avatar. More precisely, the experiment was divided into three successive phases: the first exposure phase, followed by the main experiment phase, and finally the last exposure phase.

- First exposure phase: The first exposure phase was conducted to allow the users to be accustomed to the shared body control and experimental environment (see Figure 4.3). Moreover, we took advantage of this phase to evaluate users' SoA and SoBO to assess their level of embodiment when possessing full (independent body) or half control (shared body) over the virtual avatar.
- Main experiment: To explore the influence of the level of shared control toward the avatar on

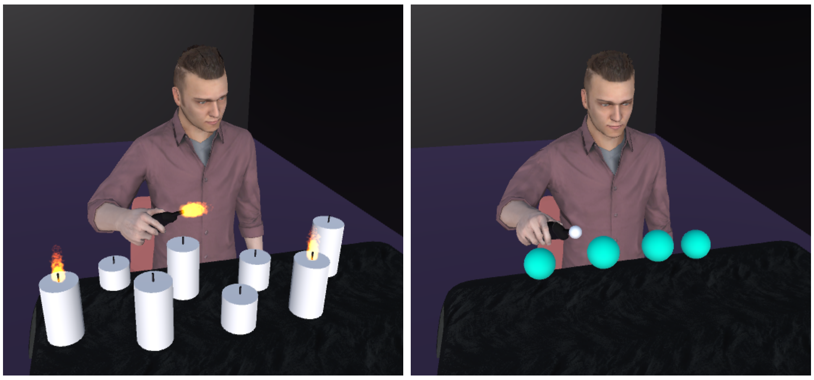


Figure 4.3 – Exposure phase in which participants were asked to light candles (left); main experiment in which participants were asked to touch some spheres with the tip of their controller (right). Images are shown from third-person perspective for illustrative reasons.

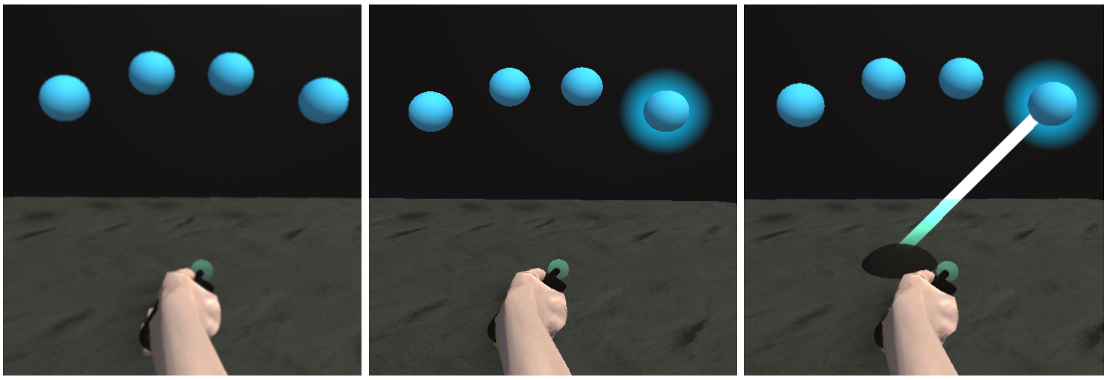


Figure 4.4 – The three tasks that the users were asked to perform. Free task: participants had to choose which sphere to touch (left). Target task: the sphere that the participants were to touch was highlighted (center). Trajectory task: the sphere to touch was highlighted and participants had to follow a path from the table to the sphere with the tip of their controller (right).

the SoA, five controlling weights were considered between 0% and 100% (with a 25% step). In addition, to evaluate the influence of the freedom of movement and the intention toward an action on the SoA, three tasks were considered (Figure 4.4).

- Last exposure phase: This phase was conducted to evaluate potential training effects of the main experiment over agency and ownership ratings.

4.4.2 Participants

Twenty-four male participants from the university campus participated in the experiment [age: $M = 26 \pm 5$ (SD)]; they were recruited from among both students and staff. They were all unaware with respect to the purpose of the experiment, had normal or corrected-to-normal vision, and gave written and informed consent. The study conformed to the declaration of Helsinki. The participants were paired with those they had never interacted with prior to the experiment. Among the participants, seven had no previous experience with VR, fourteen had limited previous experience, and three were familiar with VR. All participants were right-handed male Caucasians, to match the visual appearance of the virtual avatar as much as possible.

4.4.3 Experimental Protocol

The overall organization of the experiment is summarized in Figure 4.5 and is further described as follows.

Upon their arrival, participants read and signed the experiment consent form and filled in a demographic questionnaire. They also completed the IPC cognitive test [Hanna 1974]. The internal score computed from this test was used later to measure LoC and explore its influence on the SoA. Then, they were briefed about the experiment through an explanatory video. They were explained that they would share a body and control over it with the other participant. After the explanation, they were instructed to sit on a chair in front of a table facing each other and wear an HMD to get immersed in the VE (Figure 4.2).

As previously explained, the experiment was divided into three phases, which the participants experienced in order: the first exposure phase, main experiment, and last exposure phase. In addition, while participants were immersed in the VE, they were instructed not to talk or interact with each other. As the tasks to perform only required motions of the right arm, we decided to focus on the right arm and did not animate the left arm. Participants were therefore asked to keep their left arm along their torso and not move it. After the experiment, they were instructed to remove their HMDs and provide general comments and feedback through a web form. The overall process took approximately 1 h.

4.4.3.1 First and last exposure phases

Participants started with the first exposure phase and finished with the last exposure phase, in which they were asked to light candles using a virtual lighter (Figure 4.3, left). Once participants had lit all their candles, the candles would extinguish, and the participants were asked to light them again. This task lasted for 2 min, and each phase was repeated twice (2 blocks): once with half of the avatar control for each participant, and once with full control over their own avatar. Each block would finish with an ownership and an agency questionnaire, which consisted of 11 items (Table 4.1); the participants answered based on a scale ranging from 1 to 7 by pressing buttons on the controller in their hand. Each participant thus answered the questionnaires four times.

4.4.3.2 Main experiment

In the main experiment, the avatar was always shared and the weight of avatar control for a participant varied between 0% and 100% (respectively 100% minus this weight for the other participant). We considered five weights between 0% and 100% (with a 25% step) to evaluate how differences in the degree of control would impact participants' SoA. Thus, we hypothesized that the SoA would be positively correlated with the degree of control.

Participants were asked to perform three tasks involving touching one virtual sphere among four spheres, with the extremity of the virtual controller held in the right hand. Four spheres were presented in front of the participants, all at equidistance from their right hand. More precisely, by using the original 3D model of the HTC Vive controller, we attached a short rod with a small sphere on top; this tip collided with the sphere (Figure 4.3, right).

There were three types of tasks: free, target, and trajectory. The different tasks contrasted from each other with respect to the freedom of movement they allowed and whether both participants possessed the same prior knowledge of the same action to perform. More precisely, in the free task, each participant was free to choose which sphere to touch (Figure 4.4, left). In the target task, the sphere to touch was imposed and highlighted with a colored halo (see Figure 4.4, center). Similarly, in the trajectory task, the sphere to touch was imposed and highlighted, and the participants were asked to follow a displayed path from the table to the highlighted sphere by using the tip of the controller; this task required more precision (see Figure 4.4, right).

These three tasks were selected in line with the hypothesis that constraints in the movements and prior knowledge of the action to perform (i.e., the intention toward the action) both impact the SoA. In the free task, each participant was free to choose which sphere to touch (Figure 4.4, left), under a condition where the movement of participants was not restricted and where the movement intention was not assuredly shared as participants might not decide to touch the same sphere. In the target task, the sphere to touch was highlighted with a colored halo (Figure 4.4, center), under the condition that the movement was not restricted and the movement intention was shared as both participants focused on touching the same sphere. In the trajectory task, the sphere to touch was highlighted and participants were to follow a path from the table to the sphere by using the tip of the controller. This task required more precision (Figure 4.4, right), and included both movement restriction and the shared intention, as participants had to follow a specific path to touch the same sphere.

These choices were driven by the demonstration of previous studies that SoA increases when participants have more action choices [Barlas et al. 2017]. However, in our case, owing to changes in the level of control over the avatar, the more the participants had the choice of the action (in the free task compared to the target and trajectory tasks), the more the visuomotor discrepancies were expected between participants and avatar movements. We thus supposed that the SoA would be higher for the target and trajectory tasks with smaller visuomotor discrepancies. Considering the results of Wegner et al. [2004], we also expected that SoA would be higher in tasks where the intention of movement was shared (in target and trajectory tasks compared to free task).

In each task, participants performed 45 trials. For each trial, the participants started observing their own avatar over which they had full control. To ensure that both participants had the same initial position, they were asked to place their right hand holding the controller on the table on a specific virtual reference and to remain on the initial reference. After 2 s, the four spheres were displayed in red with a message “don’t move yet”. The message disappeared after 2 s, the spheres turned blue, and then the participants could perform the task. When a sphere (any of the four spheres for the free task, specified sphere in other tasks) was touched for 1 s by the tip of the controller of the shared avatar, the task was over and the following question was asked to both participants: “On a scale ranging from 1 to 7, how much did you feel in control during this trial?”. As such, we followed the same protocol as that used by Jeunet et al. [2018] to assess the SoA through a question that is easily understandable by participants and proved to relate to the judgment of agency. Participants provided a rating between 1 and 7 to validate their choice using the controller. When both participants had answered the question, they were asked to place their hand on the highlighted spot to start the next trial.

4.4.4 Experimental Design

4.4.4.1 First and Last Exposure Phases

A within-subject design was set up for these experimental phases, where we considered two independent variables: Control and Stage. The main variable (Control) considered whether the participants were sharing the avatar, and possessed two levels: 1) participants sharing the avatar with 50% control each (*Half*) or 2) participants having full control over their own avatars (*Full*). The Stage variable determined whether the task was completed in the first or last part of the experiment, and thus had two levels: *First* and *Last*. This part of the experiment was divided into two blocks corresponding to the two levels of the control condition. In both first and last exposure

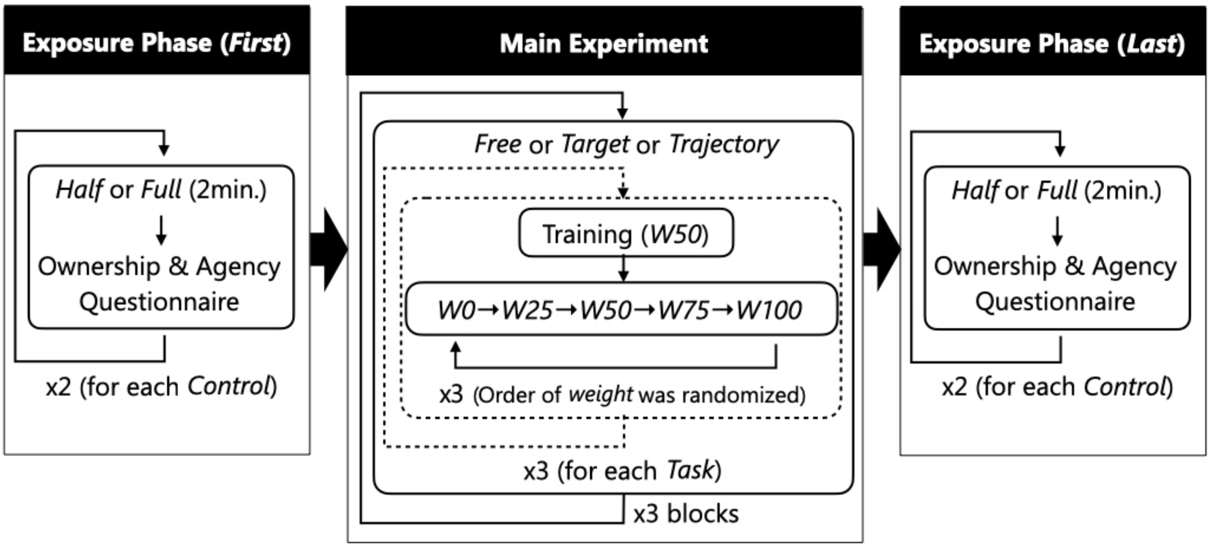


Figure 4.5 – Diagram of experimental flow.

phases, whether participants would start with one block or the other was fully counterbalanced in the experiment.

The measured data (dependent variables) in a questionnaire were inspired from previous work [Botvinick and Cohen 1998; Longo, Schüür, et al. 2008; Kalckert and Ehrsson 2014; González-Franco and Peck 2018], where questions were divided into two groups: agency and ownership (Table 4.1). For each question, participants were asked to provide rating based on a 7-point Likert scale. Based on previous works showing that asynchronous visual information in relation to participants' own movements affects both SoBO [Banakou and Slater 2014; Kalckert and Ehrsson 2012; Ma and Hommel 2015] and SoA [Franck et al. 2001; Farrer, Bouchereau, et al. 2008], our main hypothesis was that participants would have lower agency and ownership when they had only half control than when they had full control of their avatar.

4.4.4.2 Main Experiment

We also adopted a within-subject design for the main part of the experiment, considering two independent variables: Weight and Task. The Weight variable determined the degree of control the participants had over the avatar and had five levels (*W0, W25, W50, W75,* and *W100*). For each pair, Weight was inverted between participants, i.e., the sum of the controlling weights of the two participants was always 100%. Task corresponded to the three tasks included in the experiment (*Free, Target*, and Task; see Section 4.4.3.2 for details). The main experiment was divided into three blocks. To minimize the ordering effect, the orders of the blocks and

Table 4.1 – Questionnaire used in the first and last exposure phases. Questions in italics are control questions regarding agency and ownership.

Variable	Question
Agency	1) The virtual arm moved just like I wanted to, as if it was obeying my will. 2) I felt as if I was controlling the movement of the virtual arm. 3) *I felt as if the virtual arm was controlling my will.* 4) *I felt as if the virtual arm was controlling my movements.* 5) *I felt as if the virtual arm had a will of its own.* 6) I felt as if I was causing the movement I saw.
Ownership	1) I felt as if I was looking at my own arm. 2) I felt as if the virtual arm was part of my body. 3) I felt as if the virtual arm was my arm. 4) *I felt as if I had no longer a right arm, as if my right arm had disappeared.* 5) *I felt as if the virtual arm was from someone else's body.*

tasks were counterbalanced following a Latin square design. Each iteration of Task in one block comprised one training trial (with half control of the avatar) and three repetitions of the five trials (for the five levels of Weight). The order of Weight levels within the three repetitions was fully counterbalanced. Without considering the training trials, each participant performed 135 trials. Each trial lasted around 3 s.

The measured data (dependent variables) considered the performance and behavioral measurements. Regarding performance, we measured task-completion time, i.e., the time required to select the sphere after it turned blue (in seconds). Regarding behavioral measures, the motions (position and orientation per frame) of the participants' and shared avatar's controllers were recorded during the trials. Finally, the subjective FoC ratings for the question, "How much did you feel in control?" asked after each trial were rated on a 7-point Likert scale. Participants also reported general comments and feedback at the end of the experiment.

In summary, considering our experimental design, our main hypotheses are as follows.

H1 When the degree of control (Weight) decreases, the FoC ratings decrease.

H2 The FoC ratings will be higher for the tasks in which movements are more constrained (Trajectory > Target > Free).

H3 Participants with a higher Internal score of LoC experience higher FoC.

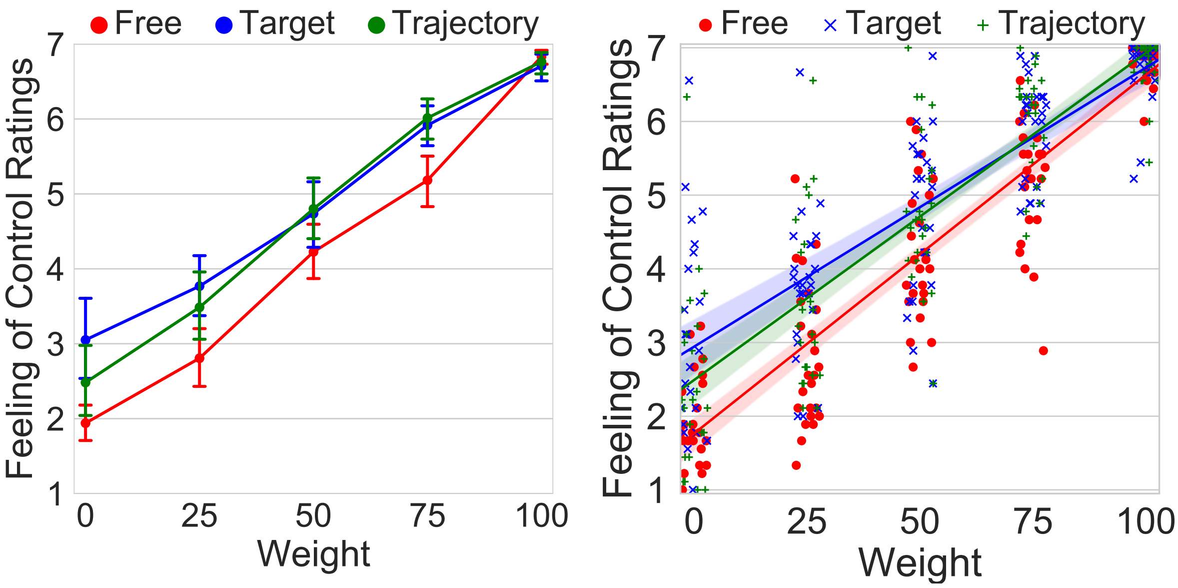


Figure 4.6 – Left: Line plot of the mean subjective ratings of Feeling of Control (FoC) considering Weight of control and Task during main experiment. Right: Scatter plots with linear regression lines of FoC ratings on Weight for each task (*Free*: R^2=0.83, *Target*: R^2=0.66, *Trajectory*: R^2=0.74). Error bars (left) and translucent bands (right) indicate 95% CIs. A total of 10,000 bootstrap samples were used to estimate each 95% CI.

4.5 Results

4.5.1 Main Experiment

Eleven trials out of all 3240 trials were excluded from the analysis after a visual inspection of the raw data revealed that either the task completion time, participant motion, or motion of the avatar exhibited abnormal values (values outside the range of three standard deviations from the mean). ANOVA analyses were conducted when the normality assumption (Shapiro–Wilk's normality test) was not violated ($p > .05$). In particular, two-way ANOVA analyses with repeated measures were conducted, considering the within-group factors of Weight (5 levels: *W0*, *W25*, *W50*, *W75*, and *W100*) and Task (3 levels: *Free*, *Target*, and *Trajectory*). When the sphericity assumption was violated (Mauchly's sphericity test), the degrees of freedom were corrected using the Greenhouse–Geisser correction. In addition, η_p^2 was provided for the quantitative comparison of effect sizes. Finally, Tukey's post-hoc tests ($\alpha = .05$) were conducted to check the significance for pairwise comparisons of the parametric data.

When the normality assumption was violated (Shapiro–Wilk's normality test, $p < 0.05$), Friedman test was conducted for each task independently followed by a post-hoc Wilcoxon-signed ranks test. For multiple post-hoc comparisons, Holm correction was applied for the non-parametric data. As for the correlation analyses, Pearson's r (r) was used for parametric data and Spearman's r (r_s) was used for non-parametric data.

4.5.1.1 Feeling of Control (FoC)

The two-way ANOVA analysis revealed a significant main effect of Task ($F_{1.84,42.37} = 17.07$, $p < .001$, $\eta_p^2 = 0.43$) and of Weight ($F_{2.4,55.15} = 256.86$, $p < .001$, $\eta_p^2 = 0.92$). However, the two-way ANOVA also exhibited a significant interaction effect between Task and Weight ($F_{5.22,120.01} = 6.30$, $p < .001$, $\eta_p^2 = 0.22$). First, Tukey's post-hoc tests indicated that, for all tasks, the FoC significantly decreased as the degree of control (Weight) decreased ($p < .001$ for all), which is further supported by the primary effects on Weight. Thus, this result supports **[H1]**. Next, when comparing the FoCs for each Weight level (see Figure 4.6 left), Tukey's post-hoc tests demonstrated that, for the *W0* Weight, the FoC was significantly higher for the *Target* task than for the other tasks (both $p < .05$).

In contrast, for the *W25*, *W50*, *W75* levels of Weight, the FoC was significantly lower for the *Free* task than for the other tasks (all $p < .05$). Finally, for the *W100* Weight, the post-hoc tests did not exhibit any significant difference. Thus, these results only support **[H2]** partially, as although the *Free* task (the less constrained task) consistently obtained the lowest FoC ratings (except for the *W100*), this effect was not visible between *Target* and *Trajectory* tasks.

As the ANOVA analysis indicated that the strongest effects originated from the Weight factor, to further characterize the relationship between FoC and the Weight factor, a linear regression analysis was conducted across participants for each task (Figure 4.6 right). The regression equations were

$$\begin{aligned} \textit{Free}&: y = 0.0487x + 1.77 (R^2 = 0.83) \\ \textit{Target}&: y = 0.0379x + 2.94 (R^2 = 0.65) \\ \textit{Trajectory}&: y = 0.0444x + 2.49 (R^2 = 0.73). \end{aligned}$$

The regression equations exhibited linear positive correlations between the FoC and the Weight. To determine whether the computed slopes differed significantly from 0, we computed the slope of each participant's linear regression and conducted a t-test (H_0: Slope is equal to 0): (*Free*: $t(23)$=35.665, $p < .001$, *Target*: $t(23)$=13.219, $p < .001$, *Trajectory*: $t(23)$=16.622, $p < .001$). The results of the t-test indicated that the mean slopes all significantly differed from 0. These results further support **[H1]**. Section 4.5.2 further analyzes the FoC ratings in correlation

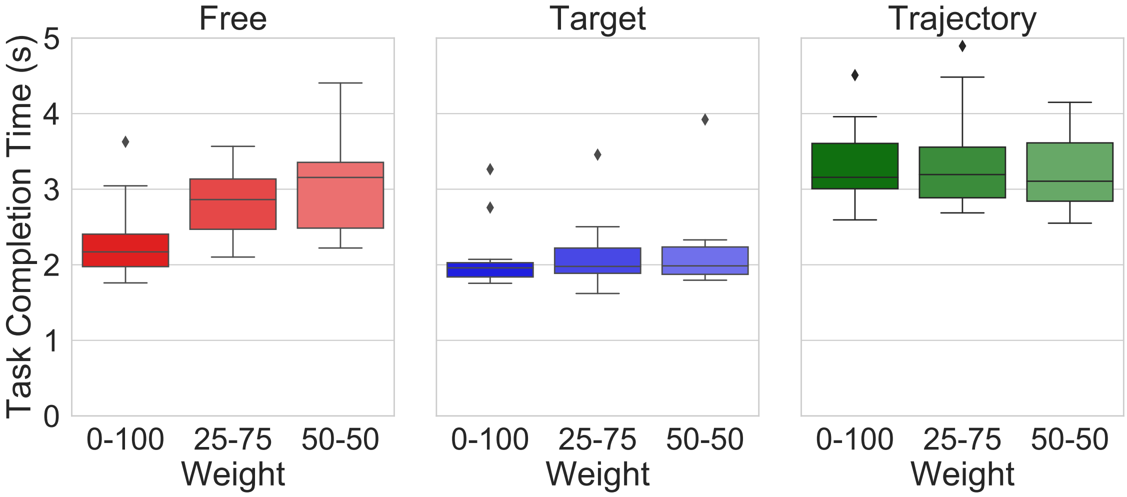


Figure 4.7 – Box plots of the task completion time considering the different Weight groups for each task.

with the IPC scores.

4.5.1.2 Task Completion Time

Because the task completion time was dependent on the weights of the two participants (their sum adding to 100%), for the task completion time analysis, the Weight group factor had only three levels: *W0-W100*, *W25-W75*, and *W50-W50* (see Figure 4.7). In addition, owing to the different natures of each task (aimed movement, path following task), we did not assess the differences among Tasks for the task completion time. Therefore, we conducted three Friedman tests considering Weight group as a factor, one for each task. The Friedman tests exhibited significant differences among the task completion times of the Weight groups only for the *Free* task (χ^2=14, $p < .001$), and no significant differences were found for the *Target* task (χ^2=0.17, $p = .92$) or the *Trajectory* task: (χ^2=3.5, $p = .17$). Post-hoc pairwise comparisons indicated that for the *Free* task, the task completion time was significantly smaller in the *W0-W100* condition (W0-W100 < W25-W75: Z=-2.81, p<.01, W0-W100 < W50-W50: Z=-3.30, p<.01). No significant differences were found between *W25-W75* and *W50-W50* (Z=-1.68, $p = .092$).

4.5.1.3 Motion Data

The offsets (Euclidean distance) between the positions of the participant's and avatar's hands were calculated for each frame and then averaged for each trial (see Figure 4.8). This value provided a rough estimate of the overall visuo-motor discrepancies for each trial. We excluded the *W100* condition from the analysis as the discrepancy was 0 regardless of the Task (condition with full control). The residuals did not follow a normal distribution; thus, Friedman tests were considered. In addition, the analysis considered each Task independently. Friedman tests exhibited significant differences of the mean offsets among Weights for all Tasks: (*Free*: χ^2=56.75, $p < .001$, *Target*: χ^2=67.25, $p < .001$, *Trajectory*: χ^2=61.85, $p < .001$). Post-hoc pairwise comparisons indicated that the mean offsets were significantly smaller when the Weight was larger for all comparisons in all Tasks (p<.001 all) except for the comparison between offsets in the *W0* and *W25* conditions for the *Free* task.

An additional correlation analysis was performed to assess the link between the mean offset across all weights and the perceived FoC. The correlation analysis revealed that the offsets were negatively correlated with FoC for all Tasks: *Free*: r_s=-0.84, p<.001, *Target*: r_s=-0.84, p<.001, *Trajectory*: r_s=-0.83, p<.001) (See Figure 4.9). Moreover, to check if the mean offsets would vary between tasks, another analysis was performed for each weight. Friedman tests revealed significant differences among the mean offsets of Tasks for W0 (χ^2=28.58, $p < .001$), W25 (χ^2=32.33, $p < .001$), W50 (χ^2=37.33, $p < .001$), and W75 (χ^2=32.33, $p < .001$). Post-hoc pairwise comparisons showed that for W0, W25, W50, and W75 the mean offsets were significantly higher for *Free* compared to *Target* and *Trajectory* (both p<.001).

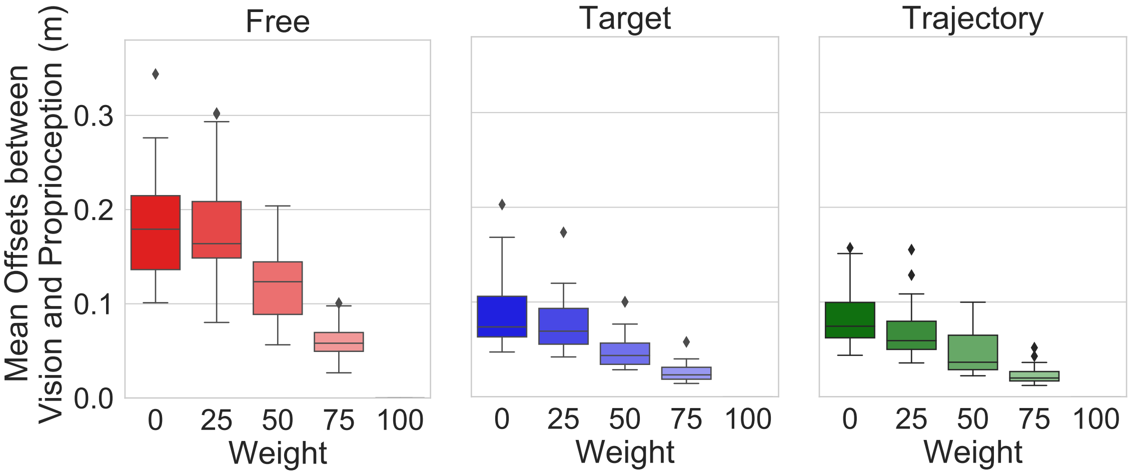


Figure 4.8 – Box plots of the mean offsets between the positions of the avatar's hand and the participant's actual hand considering the Weight for each Task.

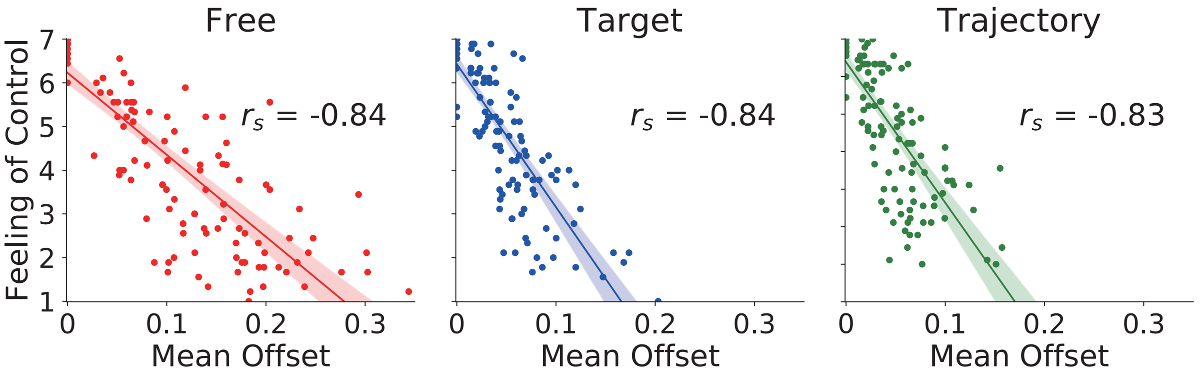


Figure 4.9 – Scatter plots with linear regression lines of FoC ratings on mean offsets between the positions of the avatar's hand and the participant's actual hand for each Task. Translucent bands indicate 95% CIs.

Finally, to gain some insight regarding the global behavior of users during each trial, speed profiles were computed for each participant per Weight and Task for each trial (see Figure 4.10). Speed profiles were normalized in time by resampling the values at 100 intervals between the start (time 0%) and end of the trial (time 100%). We then computed the mean and standard deviation of the speed profiles between all participants. To compare the speed profiles for each Task and for each interval, we conducted a Friedman test considering Weight as a factor. Tasks were not compared among each other as the nature of each Task was different. Among those intervals, post-hoc pairwise comparisons (Wilcoxon signed-rank tests) were performed to find pairwise differences among different Weights. The results of pairwise comparisons are also summarized in Figure 4.10, in which each Weight is denoted by a color; lighter colors are associated with lower Weights and vice-versa, and colored segments are placed at the intervals in which significant differences were found. Thus, the presence of a colored segment indicates that a significant difference ($p < .05$) was found between the current interval and the corresponding interval of the color-coded condition.This result allows us to highlight the tasks in which changes in the control induced differences in participant behavior. For example, for *Target* and *Trajectory* tasks, the Weight seems to only have a visible impact at the end of the motion, in particular for *W0* and *W25*, whereas more discrepancies were found for the *Free* task.

4.5.2 Locus of Control

According to the responses of the IPC test, each participant obtained three scores (from 0 to 48), one for each dimension of the IPC test (i.e. Internal, Powerful Others, and Chance). Each score was calculated by adding the responses of the eight items for each dimension and a constant of 24. Similar to previous studies, only the Internal dimension was assessed [Jeunet et al. 2018], as it was found to be the dimension that was more related to the FoC. A high rating on the Internal score indicates that the subject has a strong internal Locus of Control (i.e., they believe that events in their life derive primarily from their own actions).

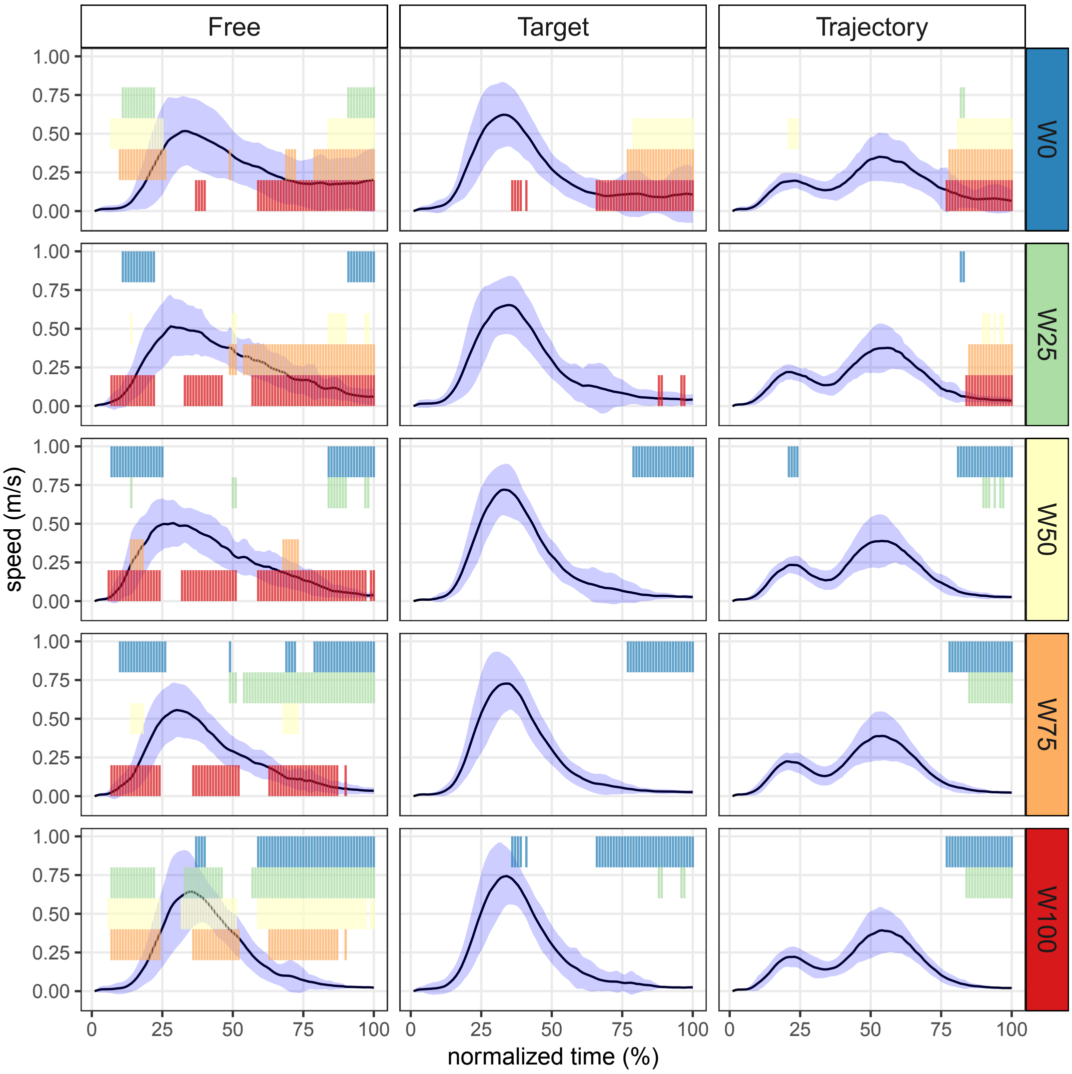


Figure 4.10 – Averaged Speed profiles between all participants for each Weight and Task, normalized in time and re-sampled at 100 intervals. Colored segments were placed at intervals in which significant differences (Friedman and Wilcoxon pairwise comparison tests) were found. Colors are associated to a specific Weight.

First, to verify whether participants with higher internal score of IPC tended to experience higher FoC when they had full control (W100), we conducted a correlation analysis between the internal scores and the mean FoC scores in the W100 condition for each task. As a result, no significant correlation was found between the internal score and the FoC: *Free* (r_s=0.23, p

$= .29$), *Target* (r_s=0.33, $p = .11$), *Trajectory* (r_s=0.25, $p = .23$). This result might be explained by a ceiling effect of very high values of FoC in the W100 condition. This result does not support **[H3]**.

In contrast to previous studies, the modulation of the participant's control was quantified by the Weight parameter. This enables us to analyze the correlation of the internal component of the IPC with the FoC in a wider range of FoC values. First, as already detailed in Subsection 4.5.1.1, we computed the correlation between the Weight and the FoC for each participant. The intercept coefficient could be considered as the FoC "baseline," while the slope could be related to the "sensitivity" to changes in the participant's control. In other words, the slope provides information on how much the change in the participant's control influences the FoC, and the intercept provides a lower bound for the FoC. In practice, in our scenario, both parameters are strongly correlated because there is a strong ceiling effect for the FoC at W100. Thus, we computed the regression equations of FoC on Weight for each participant and performed correlation analyses of both the slopes and intercepts with the participants' score of the Internal dimension of the Locus of Control (from the IPC test). The results show a positive correlation between the slope and the Internal dimension for each Task (*Free*: r=0.54, p<.01, *Target*: r=0.47, p<.05, *Trajectory*: r=0.49, p<.05, see Figure 4.11 up), as well as the negative correlation between the intercept and the Internal dimension for *Target* and *Trajectory* tasks (*Target*: r=-0.44, p<.05, *Trajectory*: r=-0.47 p<.05), and a marginally significant effect for the *Free* task (r=-0.40, p=.05) (See Figure 4.11 down).

These results seem to suggest that participants with a higher Internal score were more sensitive to changes in the avatar control as they had lower intercept values and higher slope values.

4.5.3 First and Last Exposure Phases

The agency and ownership ratings for the *First* and *Last* exposure phases were aggregated and averaged (control item answers were inverted) to compute one agency and one body ownership score per participant. Owing to the non-parametric nature of the data and the need of testing interaction effects, we applied an aligned rank transform (ART) on the data. This procedure enables the use of ANOVA to analyze the interaction effects with non-parametric data [Wobbrock et al. 2011]. Two-way repeated measures ANOVAs with the within-subjects factors Control (2 levels: *Half* and *Full*) and Stage (2 levels: *First* and *Last*) were performed for both agency and ownership scores. Regarding the agency scores, the ANOVA revealed a significant main effect of Weight ($F_{1,23} = 198.41$, $p < .001$, $\eta_p^2 = 0.90$) and Stage ($F_{1,23} = 19.22$, $p < .001$, $\eta_p^2 = 0.46$)

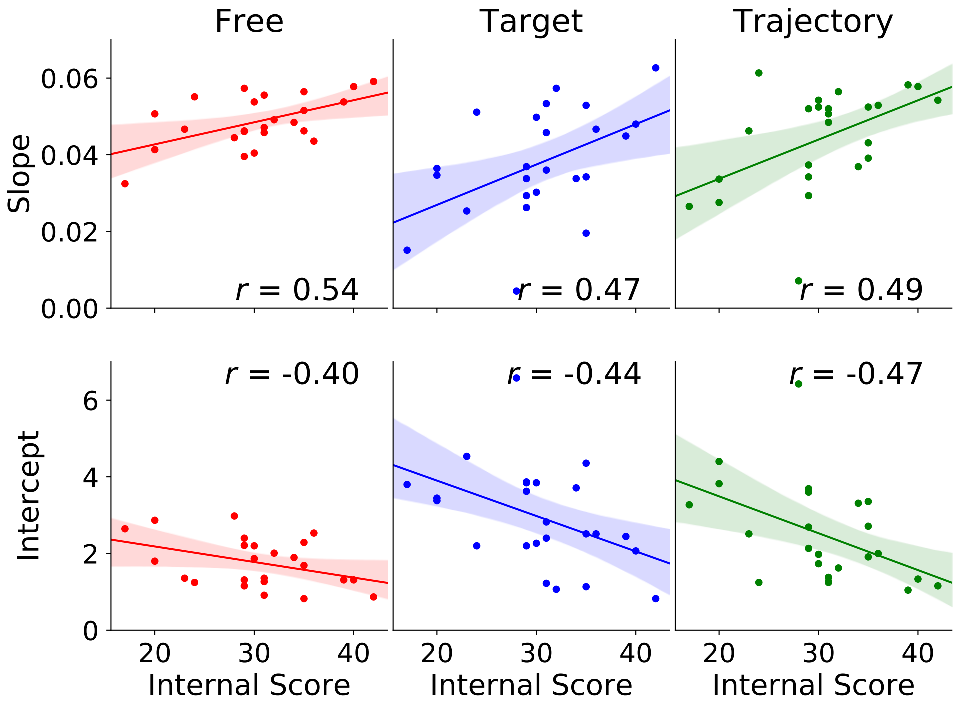


Figure 4.11 – Scatter plots with linear regression lines between the internal score of the IPC test and the regression coefficient terms obtained between the FoC ratings and Weight for each participant (slope (top) and intercept (down)). Translucent bands indicate 95% CIs. 10,000 bootstrap samples were used to estimate each 95% CI.

(Figure 4.12 Left). In addition, the Weight × Stage interaction effect was significant ($F_{1,23} = 5.17$, $p < .05$, $\eta_p^2 = 0.18$). Thus, we only report the post-hoc tests for the interaction effect. First, post-hoc pairwise comparisons using the Wilcoxon signed-rank test (Holm corrected) showed that in both *First* and *Last* phases the agency scores were significantly higher in the *Full* condition than in the *Half* condition (*First*: Z=-5.29, p<.001, *Last*: Z=-5.29, p<.001). Second, in both *Full* and *Half* conditions, the agency scores were higher in the *Last* than *First* phases (Full: Z=-2.58, $p <$ .05, Half: Z=-2.09, $p < .05$).

Regarding the ownership scores, the ANOVA showed a main effect of Weight ($F_{1,23} = 84.96$, $p < .001$, $\eta_p^2 = 0.79$) and a marginally significant main effect of Stage ($F_{1,23} = 3.78$, $p = .06$, $\eta_p^2 = 0.14$) (See Figure 4.12 Center). The Weight × Stage interaction effect was not significant ($F_{1,23} = 0.68$, $p = .42$, $\eta_p^2 = 0.03$). Similar to the agency ratings, the ownership scores were significantly higher for the *Full* condition. In addition, we conducted a correlation analysis between the agency and the ownership scores for each participant, showing that ownership was positively correlated with agency in the *Half* condition (r_s=0.54, p<.01), but not in the *Full* condition (r_s=0.31, p = .14) (See Figure 4.12 Right).

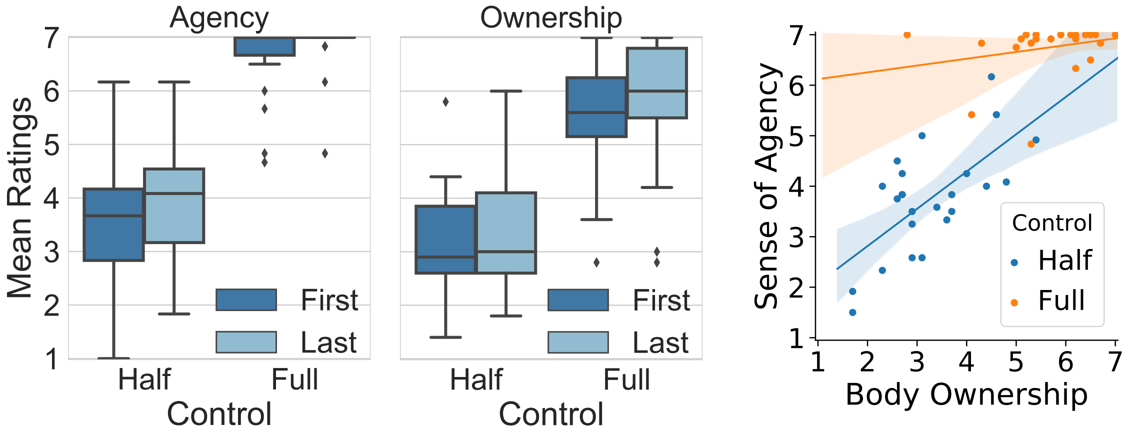


Figure 4.12 – Box plots of mean ratings of agency (Left) and ownership (Center) obtained in the questionnaires in *First* and *Last* exposure phases. Right: Scatter plots with linear regression lines of agency ratings on ownership ratings. Translucent bands indicate 95% CIs. 10,000 bootstrap samples were used to estimate each 95% CI.

4.6 Discussion

In this section, we discuss how the results can be interpreted in terms of SoA, which is measured by subjective judgments of FoC over the participants' actions. We also provide additional insights regarding the Locus of Control and the relation between SoA and SoBO.

4.6.1 Main Results

The SoA results show that changes in the degree of control clearly influenced the SoA, which validated **[H1]**. More precisely, the FoC ratings, which were treated as an explicit measure of the SoA according to previous studies [Wegner, Sparrow, et al. 2004; Linser and Goschke 2007], increased linearly with the increase in the degree of control for all three tasks. This result can be explained by the fact that the higher the degree of control is, the closer the visual feedback of the avatar hand is to the actual hand position of the participant, thereby reducing visual mismatch between the movements of the avatar and the participants' actual movements. As stated by Farrer et al. [2003], our ability to recognize SoA from the visual cues of movement tend to decrease in case of mismatch between visual feedback and actual movement, i.e., when there are visuo-proprioceptive discrepancies, which could justify the correlation observed between the SoA and the degree of control. The participants' feedback is also in line with this interpretation, as they expressed their disturbance when their arm was controlled out of their will: "*It was confusing when the hand was going in the direction I intended it to go but the speed did not totally match my movements*". These results can also be explained by the phenomenon of "body semantic violation" introduced by Padrao et al. [2016]. In our case, it refers to the fact that the agency illusion will break when the discrepancy between feedback and intended motion becomes too important.

Another interesting result reveals that when participants had no control over the avatar (W0), the SoA was higher for the Target task than for the Free and Trajectory tasks. While we hypothesized that the nature of the task could influence the perceived SoA, the tasks differed in two main aspects. The first difference relates to whether participants shared an intention toward the action to perform. In the Target and Trajectory tasks, the sphere to be touched was indicated, meaning that both participants shared the same intention of action: touching the same sphere. On the contrary, in the Free task, participants could have different spheres to touch in mind; this sometimes resulted in a difference between the intention, the sphere a participant wanted to touch, and the resulting action, the sphere finally touched by the shared avatar. According to Wegner et al. [1999], SoA arises if (1) an intention precedes an observed action (priority), (2) the intention is compatible with this action (consistency), and (3) the intention is the most likely cause of this action (exclusivity). In the Target and Trajectory tasks, the three principles of priority, consistency, and exclusivity are more likely to be respected as participants share the same intention. Independently of their degree of control, the controller of the shared avatar will therefore reach the targeted sphere. This would support why SoA ratings where higher in the Target and Trajectory tasks when participants had no control over the shared avatar. The second difference was in the visual difference between participants and avatar hand positions (See Figure 4.8) depending on the task. Indeed, results showed for example that visuo-motor and visuo-proprioceptive discrepancies were lower in the Target task compared to Free when participants had no control. This can be because in the Target task, participants have the indication of which sphere to touch, resulting globally in the same movement toward the target sphere. Following the statements of Farrer et al. [2008] that visuo-motor discrepancies tend to decrease the SoA, this could explain why the SoA was higher in Target than in the Free task where participants had no control at all. However, these results only partially support **[H2]**.

Furthermore, a surprising result is that in the Target and Trajectory tasks, participants tended to overestimate their SoA, feeling some SoA despite the absence of control. From the analysis of speed profiles, we observed that major differences between control weights were found in the Free task, whereas only some differences were observed in the Target and Trajectory tasks, mostly at the end of trials. This seems to show that participants tended to have similar reaching behaviors regardless of their degree of control in the tasks where the goal was shared. Other authors also observed that the SoA was affected when the avatar's and the participant's speed of movement differed [Kokkinara, Slater, and López-Moliner 2015], but not with spatial shift of movement without speed alteration. These results could explain why participants tended to overestimate their SoA in the Target and Trajectory tasks, as we can see that even with no or very low control, participants still performed the task in a similar manner, therefore minimizing spatio-temporal discrepancies.

We also observed during the experiment that some participants reported a pure illusion of the control: "*Sometimes, when the task was accomplished in an excellent manner, I wondered if it was actually me who had moved the arm* ". It is known how high-level contextual information (whether participants believe that the outcome is either triggered by themselves or by somebody else) can influence intentional binding [Desantis et al. 2011], referring to the implicit measure of the conscious experience of SoA [Moore and Obhi 2012]. Depending on whether participants were more or less aware of their degree of control over the avatar may have affected their SoA. Furthermore, another feedback particularly illustrates potential future studies: "*I had the impression that sometimes no one controlled my movement and that I was actually watching a video*". Indeed, sharing the control of the avatar with an autonomous virtual agent instead of another person would be an interesting topic to explore, in line with other studies which explored the influence of human and computer co-actors over the SoA in joint actions [Obhi and Hall 2011]. In particular, they showed that SoA for self-generated actions was inhibited when the participants knew that a computer was the co-actor of the action, which would be interesting to explore in the context of our co-embodiment setup.

4.6.2 SoA and Locus of Control

According to the results of the correlation analyses between the slope or intercept of FoC and the internal dimension of the locus of control (Figure 4.11), the intercept of the regression of FoC scores on the weight factor was negatively correlated with the Internal scores, especially when participants had little or no control over the virtual body, which does not validate **H3**. More precisely, participants with a high Internal score tend to have their feeling of agency be more impacted by changes in the level of control.

In previous studies, the Internal score was observed to be positively correlated with participants' SoA when participants were immersed in a VE and embodied in their own virtual avatar over which they had full control [Jeunet et al. 2018]. Our results do not support those findings, probably due to the ceiling effect we observed on SoA when participants had full control. However, we herein investigated the influence of the locus of control one-step further, exploring the influence of the Internal score on the SoA when participants did not have full control over their avatar. We found that participants with a high Internal score tend to have their SoA more impacted by changes in their degree of control of the avatar. People with a high Internal score are known to attribute the consequences to themselves rather than to chance or other more powerful entities and tend to believe that they have personal control over performance and rewards. However, such a definition does not commonly consider body movements. Given the little amount of previous work linking LoC and SoA, the results from such analyses should thus be treated with considerable caution. On the one hand, our results seem to suggest that people who tend to attribute consequences to themselves are possibly more aware of their own actions and thus notice more when they do not have control. On the contrary, people with a high Internal score might attribute events, movements included, to themselves and then attribute the movements of the avatar they did not cause to themselves. We would thus expect from participants to experience a high SoA even with no control over the shared avatar. While our results are in contradiction with this hypothesis, it would be in agreement with Desantis et al.'s study [2011] wherein they showed that when participants believe that they have control over the environment, intentional binding, an implicit measure of the SoA, is stronger. However, in our analysis, we only tried to correlate the Internal score with FoC, an explicit measure of the SoA. As previous findings do not always agree on whether implicit and explicit measures of agency relate to the same thing [Dewey and Knoblich 2014], it would be interesting to also consider correlating implicit measures of the SoA with the Internal score. Therefore, our results on the influence of the Internal score of the Locus of Control over the SoA demonstrate the need for further investigation on the topic.

4.6.3 Sense of Embodiment

Results from the agency and ownership questionnaires in the first and last exposure phases showed that having only half the control of an avatar significantly decreased both SoBO and SoA compared to when they fully controlled an avatar (Figure 4.12 Left and Center). Such results are in line with numerous previous studies showing that asynchronous visual information with reference to participants' own movements eliminates both SoBO [Banakou and Slater 2014; Kalckert and Ehrsson 2012; Ma and Hommel 2015] and SoA [Franck et al. 2001; Farrer, Bouchereau, et al. 2008]. In addition, our results showed that agency and ownership scores were positively correlated when each participant had half of the control of the avatar, whereas no correlation was found when they had full control over their own avatar (see Figure 4.12, right). As for the relationship between SoBO and SoA, some studies indicate that both experiences can partially double dissociate [Kalckert and Ehrsson 2012; Sato and Yasuda 2005; Braun, Thorne, et al. 2014; Tsakiris, Prabhu, et al. 2006] while some others suggest that they may strengthen each other if they co-occur [Longo, Schüür, et al. 2008; Tsakiris, Prabhu, et al. 2006; Banakou and Slater 2014; Dummer et al. 2009] (For review, see [Braun, Debener, et al. 2018]). While we observed a ceiling effect of the agency scores when participants had full control, the positive correlation found in the half condition indicates a close relationship between SoA and SoBO. Furthermore, the variability of participants' responses suggest that the subjective experience of being embodied in a shared avatar varies strongly among individuals.

Considering such positive correlations, the induction of the stronger SoBO over the virtual body can be considered to make SoA stronger and vice versa. Indeed, Kokkinara et al. [2015] observed that illusory SoA occurred despite the distortion of movements being larger than the detection thresholds of discrepancies found in previous studies. They also remarked that their results might be due to the full-body ownership illusion. In our study, Figure 4.9 indicates that in the Free task, participants felt more than half control when the distance between participant's and avatar's controller positions were below 0.1 m on average. As SoBO is known to be affected by top-down factors such as the congruence of the structural and morphological features between one's own and virtual bodies [Kilteni, Maselli, et al. 2015], making the features more congruent might therefore induce a stronger SoA. It is also considered to increase the detection threshold of visuo-motor discrepancies. In VR, some studies have exploited such visuo-motor discrepancies to enhance passive haptics or improve manipulations by changing the mapping of movements from the physical to the virtual space [Lecuyer et al. 2000; Azmandian et al. 2016; Kohli et al. 2012]. The interplay between SoBO and SoA is a subject of psychological interests, but seeking to reduce the detection threshold of visuo-motor discrepancies by strengthening SoBO might also be useful to VR applications.

In addition, there has been some evidence showing the dynamic relationship between self-attribution and sensorimotor systems. In Nielsen's study [1963], participants experienced the illusory SoA and attributed the experimenter's hand in a mirror to their own while drawing a straight line. In particular, when the experimenter distorted their movement so that he/she drew a curved line, participants still attributed the movement to themselves and moved in the opposition to the experimenter's movement to compensate for the error between the predicted and actual movements. This means that as long as they attributed a movement to themselves, they tried to control it. Asai [2015] also reported that illusory self-attribution of fake movements might coordinate sensory input and motor output. Conversely, when participants became aware of the uncontrollability of the cursor, the illusory self-attribution was also dismissed. In our experiment, the degree of control was different for each trial. Therefore, participants could not fully adapt to it. However, in case of a constant degree of control, participants might feel a stronger SoA since visuo-motor adaptation might enable participants to predict the avatar's movements. Investigation of the adaptation process of co-embodiment would therefore be necessary to further understand how to elicit higher SoA for future applications.

4.6.4 SoA in Joint Action

We perform joint actions together with others in our daily lives, e.g., carrying heavy things, and admirably coordinate our plans and actions to achieve our joint goal. Indeed, in such cases, individuals build up a shared motor plan, incorporating others' actions into their own motor system during a joint action [Obhi and Hall 2011]. In joint actions, there is therefore an automatic formation of a new agentic identity (a "we" identity) [Obhi and Hall 2011], and we feel the sense of us.

In the virtual co-embodiment situation where two individuals jointly control one avatar, as mutually coordinated actions of self and other produce the united movements, individuals might therefore also feel a sense of "us". In our experiment, we found it particularly surprising that participants were able to immediately coordinate their actions to the joint goal even with the completely novel way of interacting and the lack of verbal communication.

Nevertheless, according to participants' feedback, this collaborative behavior was not shared between all participants and some of them even tended to get the feeling of competing while performing the task: "*I felt in competition especially for the free task*", "*I sometimes felt in competition when we both had control and wanted to go on different spheres*". We also observed that the time to complete the task was higher when the control was equally shared between participants compared to when one participant had more control than the other in the Free task. Such differences could be caused by the adoption of "leader/follower" behaviours when one participant has more control that the other; however, further investigation would be necessary to explore such a hypothesis. Overall, research on virtual co-embodiment could therefore contribute to studies of joint action that investigate the mechanisms of how individuals coordinate their actions online, which is the essential capacity of humans as social beings.

4.6.5 Future Work

Despite the interesting insights gained from our experiment, we believe that there are still other aspects that would require further research.

First, our study focused on a particular virtual co-embodiment experience, namely two users sharing an avatar to accomplish simple tasks with different degrees of control. The results showed that users were able to perform the tasks and their SoA positively correlated with their degree of control. Additionally, previous knowledge of actions to be performed significantly increased their SoA. However, owing to the inter-relation of sharing the avatar and the actual degree of control, clearly quantifying the effects of each is difficult at this stage. Thus, the actual effect of being embodied in the same virtual avatar with someone else remains unclear. Does the mere fact of knowing that you share your avatar with someone else have an impact on the perception over the avatar? This is still an unanswered question that would require additional experiments, e.g., a virtual co-embodiment scenario in which a user shares the avatar with an autonomous agent.

Second, the proposed control scheme demonstrated that a partial degree of control can still elicit a SoA over a shared virtual body and that the motor actions performed in such a context resemble the ones performed with full control of the virtual body. Our implementation was meant to evaluate a novel concept, for which we tested one of the potential shared-control schemes. For example, as the shared control of the avatar head was particularly problematic, we decided that each user would keep full control of the avatar head as sharing its control might require unwanted changes at the user's viewpoint. Such situations could lead the user to be prone to motion sickness. However, in situations where users are allowed to move freely around, a more complex scheme would therefore be required as the overall shared posture might be different than the users' own posture. This would therefore require exploring more complex control schemes, techniques for switching control schemes depending on the situations and objectives, or even supporting more people embodied in the same avatar. Moreover, even at the level of controlling individual body parts, different control schemes can be considered. In our implementation, we averaged the positions and orientations of the controllers, but other methods could, for instance, explore splitting the control of different body parts or taking control depending on a certain movement threshold.

Third, virtual co-embodiment has a variety of potential applications such as remote training or entertainment. In a manner similar to our method, Yang and Kim's "Just Follow Me" [2002] method visualizes the motion of the trainer as a ghost, superimposed on the avatar of the trainee in the virtual environment. A similar method was also proposed in augmented and mixed realities for remote guidance and collaboration [Chenechal et al. 2016; Huang, Alem, et al. 2013]. In contrast, a system based on the principle of virtual co-embodiment could allow trainers to control a trainee's movements to different degrees depending on the training needs and allow them to interact with each other through body movements while sharing the same experience. The results of our study showed that even when participants had no control over the avatar, they overestimated their FoC when the situation constrained the movements and indicated a shared goal. It suggests that in the training situation, the trainee could feel SoA over their body even when the body is fully controlled by the trainer. In addition, training could be made more effective by changing the degree of control depending on the learning phase, which in turn would require designing efficient and intuitive ways to adapt the degree of control to the situation. Moreover, it would be interesting to compare the cognitive load inferred by our system with the one felt in an approach similar to the "Just Follow Me" method [Yang and Kim 2002], searching if one method is more susceptible to increase the cognitive load of the trainee while learning through an application. This will also open new opportunities to explore how mismatching the actual and announced degrees of control influences the user's SoA, e.g., by telling both users that they have a 75% control even though they actually have 50% control each. Furthermore, another potential application of virtual co-embodiment could be the tele-operation of one robot by two experts at a time, as for instance the co-manipulation of a medical robot by two surgeons. In such a scenario, we may imagine experts taking alternatively more or less control over the avatar in order to actuate the robot, giving them the possibility of making "pauses" in the manipulation, while maintaining a first-person point of view in the avatar in order to keep following the procedure easily. Such applications could also be extended and relevant for tele-operations in asymmetric telepresence systems, as the one developed by Steed et al. [2012], where several users might be immersed in the same environment with different capabilities of interacting. Overall, considering new means of making users efficiently collaborate in future applications, e.g., through the use of verbal interactions, visual cues, and interaction design, will be important.

Nevertheless, it must be emphasized that the results of this study were obtained only for male participants from the university campus (students and staff). Given that recent evidence suggests that interactions and collaboration between persons can be influenced by gender diversity (e.g., in teams [Bear and Woolley 2011], in pedestrian interactions [Basten et al. 2009]), gender might have influenced the results of our study, particularly in terms of whether the participants adopted collaborative or competitive strategies. It would be valuable to replicate our study with participants of more diverse gender and attributes.

Lastly, as virtual co-embodiment is a merging experience with someone else, it has the possibility to produce cognitive effects on users. Indeed, shared bodily experiences such as the enfacement illusion (i.e., self-other face-perception modification by synchronous multisensory stimulation) [Mazzurega et al. 2011; Tsakiris 2008; Sforza et al. 2010] are known to produce both perceptual and social binding. A stranger stimulated in synchrony was judged as more similar, physically and in terms of personality, and as closer to the self [Mazzurega et al. 2011;

Tajadura-Jiménez, Grehl, et al. 2012]. In addition, enfacement was positively correlated with the participant's empathic traits and with the physical attractiveness that the participants attributed to their partners [Sforza et al. 2010]. In this sense, co-embodiment could be used as a tool for psychological investigations of the "self".

4.7 Conclusion

In this chapter, we introduced the concept of "virtual co-embodiment", a situation that enables a user and another entity (e.g., another user, robot, autonomous agent) to be embodied in the same virtual avatar. In addition, we described an experiment that examined the influence of the degree of control of an avatar shared with another person on one's own SoA, as well as the influence of the predictability of avatar movements. Our results indicated that participants succeeded frequently in estimating their actual level of control over the shared avatar. Interestingly, they tended to overestimate their feeling of control when the visual feedback of the avatar's movements was closer to their actual movements, as well as when they had prior knowledge of the action to be performed. In addition, our results showed that participants performed similar motions regardless of their level of control. Finally, our results reveal that the internal dimension of the locus of control is negatively correlated with the participants' perceived FoC. Taken together, these findings not only corroborate and extend previous studies, but they also pave the way for further applications in the field of VR-based training and collaborative tele-operation applications in which users would be able to share their virtual body.

In the following chapter, we put aside the context of VR shared environments, and we explore the influence of VEs on the SoE by another angle. More precisely, after noticing the important use of threat introduction as an objective measure of the SoE, we realised that the fact of introducing a threat in the VE towards the avatar had never been considered as potentially influential over the SoE. We therefore explore that matter in the following chapter.

"It's as if you've been shot in the heart, Bill, but you're unaware of the hole or the loss of blood. I doubt you even heard the shot!"

John Irving, In One Person

5

Exploring the Impact of Virtual Threat on the Sense of Embodiment

Abstract:

This chapter aims at exploring the impact of threat introduction on the SoE. We therefore present an experiment in which participants were embodied in a virtual avatar, and performed a task in which a threat towards the virtual body was introduced a first time, then repeated several times through the experiment. The SoE of participants as well as their subjective response to the threat were assessed through subjective questionnaires before the introduction of the threat, after a first introduction of the threat and at the end of the experiment. A control group did the same experiment with no threat introduced during the task.

5.1 Introduction

VEs are particularly seducing in that they have the capacity to make users feel a wide range of emotions. For this reason, VR has become especially attractive for research into threat perception [Diemer et al. 2015], where it is crucial that the virtual environment succeeds in

Figure 5.1 – Overview of the virtual environment representing a factory (left), an avatar representing a user placing an ingot on the plate arrived on the conveyor lay (center) and the crusher threatening the user by suddenly going down while the user's hand is under it.

inducing emotional reactions. One of the main application of such feature is the study of virtual avatar embodiment, where the introduction of a threat is frequently used to assess users' Sense of Embodiment (SoE) towards their avatar. Indeed, the SoE is usually determined by the use of subjective questionnaires such as the one suggested by González-Franco and Peck [2018]. However, the use of objective measures of the SoE is being increasingly frequent in embodiment studies. For instance, Kilteni et al. showed that people with higher SoE experienced high behavioural changes [Kilteni, Bergstrom, et al. 2013]. Yet, the more common objective measure of the SoE remains to this day the response to a virtual threat towards the avatar. Indeed, as shown in Chapter 2, some research successfully showed that the SoE was correlated with the response to a virtual threat towards the virtual body [Yuan and Steed 2010; Zhang and Hommel 2016]. Nevertheless, while the introduction of a virtual threat in virtual embodiment studies is widely used, no research has specifically evaluated the impact of the virtual threat on the SoE. In other words, is the SoE modulated by the actual occurrence of the threat? For example, the stress induced by threats can be detrimental to cognitive functions such as spatial working or memory [Murphy et al. 1996]. More precisely, a study from Christensen et al. [2019] showed that fear induction was detrimental to the sense of agency of users towards their actions. While these studies were not conducted in VR, we may wonder if a virtual threat would impact similarly user cognitive functions and possibly their SoE. Moreover, a virtual threat has no nociceptive feedback corresponding to the event, unlike a real threat, although visual, acoustic and haptic feedback can be provided. While in most studies a threat is only introduced at the end of the experiment [Petkova and Ehrsson 2008; Guterstam and Ehrsson 2012], in other studies the threat can be repeated multiple times [Zhang and Hommel 2016]. Hence, the repetition of a threat in virtual reality may lead to decreased relevance of the illusion and thus less response from the participants. The aim of this chapter is therefore to explore the impact of threat occurrence and repeatability on the SoE and threat response.

5.2 Related Work on Threat in Embodiment Studies

In Chapter 2, we presented several works that used response to threat introduction as an objective measure of the SoE. In the following, we browse in more detail the methods of measure of threat response, the different types of threat commonly implemented and finally, we present several works in relation to the potential influence of threat on the SoE.

5.2.1 Measures of Threat Response

As mentionned in Chapter 2, early studies mainly used (Skin Conductance Response) SCR as an objective measure of threat response [Zhang, Ma, et al. 2015; Hägni et al. 2008]. However, while SCR was the most common way to objectively measure threat response, some limitations were raised by Zhang et al. [2016] saying that it cannot be differentiated if SCR measured general level of arousal or specific fear emotion. For this reason other measures of threat response have been explored. For instance, Slater et al. [2010] reproduced an out-of-body experience in IVR exploiting response to a virtual threat as an objective measure of ownership but using this time another measure: the heart-rate deceleration in response to threat. Furthemore, Erhsson et al. [2007] explored brain activity patterns than SCR to assess the link between the sense of ownership towards a rubber hand and response to a threat towards it. They successfully showed that threatening a rubber hand that feels “owned” can induce brain-activity patterns that are associated with anxiety. They also highlighted that this brain activity was similar to when the participant’s real hand was threatened. This heightened the evidence that brain activity after a threat towards a rubber hand can provide an objective measure that the rubber hand is fully incorporated into the body. While this previous study was not conducted in VR, González-Franco et al. [2014] showed in another study that when a threat is introduced towards a virtual body in IVR, brain activity (motor cortex activation) is correlated to the sense of ownership. Physical avoidance of a threat towards the virtual body was also used in IVR as a measure of ownership [González-Franco, Pérez-Marcos, et al. 2010a], where participants had to avoid a virtual fan going down in their direction. Kilteni et al. [2012] also used physical avoidance of threat, such as body defensive mechanisms, as an evidence of ownership towards virtual body parts. Other works used subjective questions [Steptoe et al. 2013] to assess the perception of threat and its link with the sense of ownership, such as an anxiety inventory (SA-I) [Zhang and Hommel 2016].

5.2.2 Types of Threat in Embodiment Studies

While the methods to assess response to threats towards a virtual body thus appear very numerous, the types of threat that were implemented so far also tend to vary. In rubber hand studies, the threat is often induced by an experimenter (e.g. bending a finger into a painful position [Armel and Ramachandran 2003] or introducing a sharp needle into the rubber hand [Ehrsson, Rosén, et al. 2008]). Yet, threats in virtual embodiment studies are rarely introduced by a third party, although some studies did use virtual characters in order to introduce a threat (e.g. a virtual character slapping the face of one's virtual body [Slater, Spanlang, Sanchez-Vives, et al. 2010]). It is thus more common in virtual reality to have the threat induced "by itself", like a virtual knife flying in the air and stabbing the virtual body [González-Franco, Peck, et al. 2014; Zhang, Ma, et al. 2015; Zhang and Hommel 2016].

In addition, the threats may also differ by the way they are introduced. A threat may be introduced with a goal of "surprise", in order to observe the direct physical response of participants to a sudden threat towards their virtual body [Zhang, Ma, et al. 2015], and may be characterized as "active threat". Otherwise, threats can also be "passive", being present in the virtual environment from the beginning, with participants needing to avoid them in order to perform the task [Argelaguet et al. 2016]. We may also characterize participants as "active" or "passive" considering that in experiments participants are asked to stand motionless while a threat is introduced towards their virtual body [González-Franco, Peck, et al. 2014], while in other experiments participants perform a task and are therefore in movement when a threat is introduced towards them [Zhang and Hommel 2016]. Moreover, virtual threats in embodiment studies also vary by their frequency and time of occurrence. Most of the time, the threats are introduced at the end of the experiment [Guterstam and Ehrsson 2012; Guterstam, Petkova, et al. 2011] but they sometimes occur repeatedly [González-Franco, Peck, et al. 2014; Ma and Hommel 2013]. Finally, we may consider the differences of feedback used in embodiment studies to accompany the threat, which may be strictly visual [González-Franco, Peck, et al. 2014] or associated with tactile stimulation [Ma and Hommel 2013] or sound [Zhang and Hommel 2016].

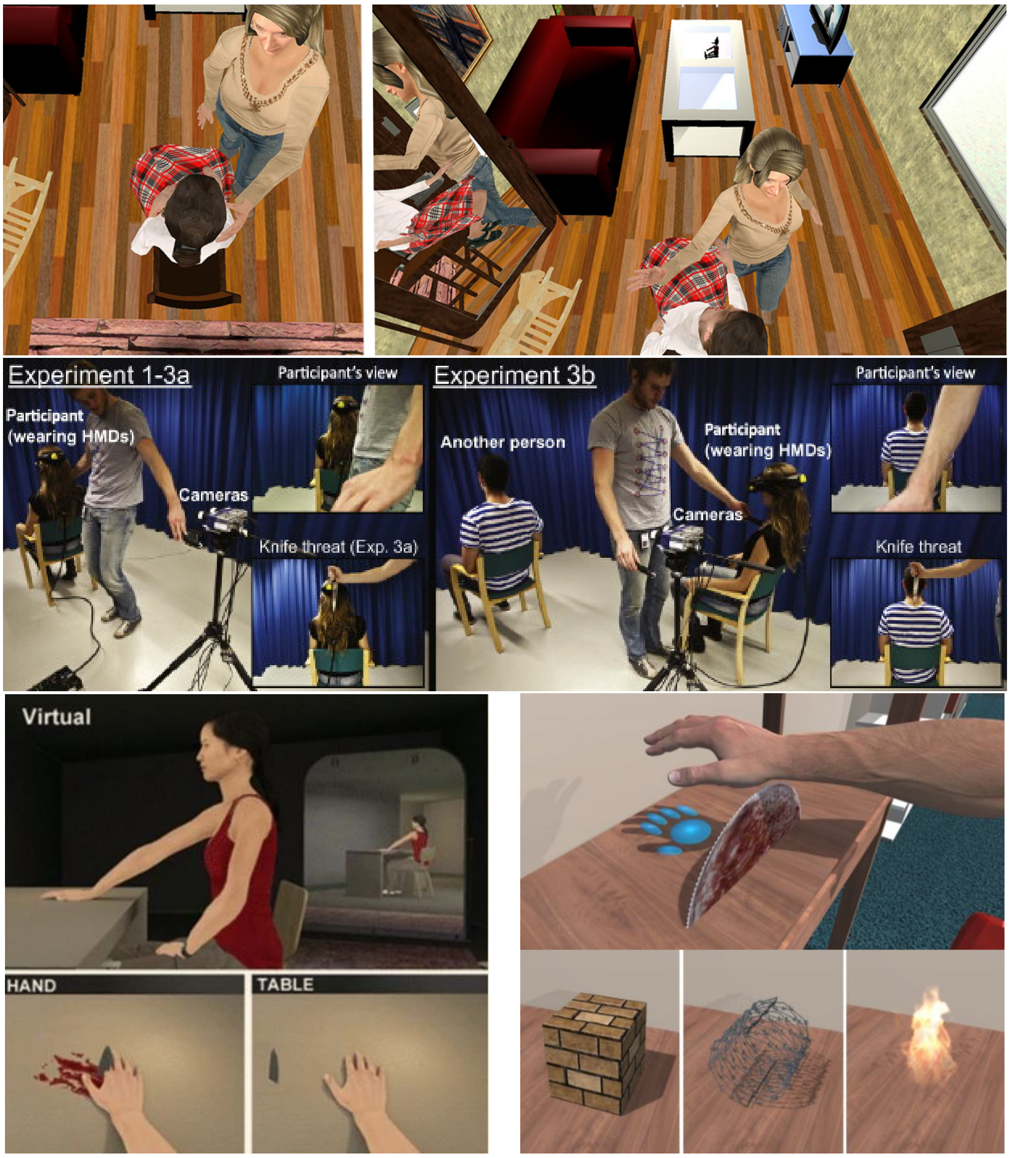


Figure 5.2 – Illustrative examples of types of threat. Top: threat from Slater et al. study [2010], on the left a woman is stroking the shoulder of the participant's avatar seen from third person point of view, on the right the woman suddenly strikes the avatar three times around the face. Middle: threat from Gusternam and Erhsson study [2012] that used a threatening knife seen behing the participant's back from third person point of view in the context of out-of-body illusion. Bottom left: threat introduced in Gonzales-Franco et al. study [2014] that consisted in a knife hurting avatar's hand stabbing from behind the table. Botton right: different threats to avoid by participants in Argelaguet et al. study [2016].

5.2.3 Impact of Virtual Threat on the Sense of Embodiment

The introduction of threat in embodiment studies has thus already been widely used as an objective measure of the SoE. Yet, no research has been conducted to evaluate the actual effect of introducing a virtual threat on the subjective measures of the SoE. Indeed, while the response to a virtual threat is used as a measure of the SoE, to our knowledge, it has never been considered as a possible influencing effect. In other words, the response to a virtual threat is associated to a strong SoE towards an avatar, but it was never verified whether its introduction could actually impact an initial SoE. However, some studies showed that stress induced by threats can be detrimental to cognitive functions such as spatial working or memory [Murphy et al. 1996]. More precisely, a study from Christensen et al. [2019] showed that fear induction was detrimental to the sense of agency of users towards their actions. While these studies do not depict the context of VR, we may wonder if a virtual threat would impact similarly user cognitive functions and possibly their SoE. Furthermore, both immersion and affective content had been shown to impact the sense of presence in virtual environments [Baños, Botella, Alcañiz, et al. 2004; Gromer et al. 2019], a cognitive feeling also widely studied to assess users' perception of virtual environments.

Additionally, in most studies a threat is only introduced at the end of the experiment [Petkova and Ehrsson 2008; Guterstam and Ehrsson 2012], although sometimes it is repeated and occurs randomly [Zhang and Hommel 2016]. Nevertheless, to our knowledge the impact of threat repeatably on its efficiency has never been assessed. Yet, when a virtual threat is induced to users in virtual reality, they may see their virtual body visually impacted by the threat (collision or even virtual blood), but have no nociceptive feedback corresponding to the event. Hence, it is possible that the repetition of a threat in virtual reality may lead to a decreased relevance of the illusion and thus a diminished response from participants.

5.3 Experiment

The main scope of this paper is therefore to explore the impact of threat occurrence and repeatability on the SoE and on threat response. The first goal was to study the potential impact of a first threat occurrence on the SoE. The second goal was to observe if the repetition of a threat would impact the way it is perceived by participants, and by extent their SoE. Therefore, in this experiment participants experienced multiple threats occurrences and their SoE was assessed through subjective questionnaires before the first threat occurrence, right after the first occurrence, and finally after all the occurrences at the end of the experiment. A control group did the same experiment with no threat introduced during the task. We also assessed participants sense of presence through subjective questionnaires at the end of the experiment in both groups, as previous work showed that fear in VR could be influenced by the sense of presence [Diemer et al. 2015], but also because both immersion and affective content have been shown to impact the sense of presence in virtual environments [Baños, Botella, Alcañiz, et al. 2004; Gromer et al. 2019].

5.3.1 Participants

Sixty participants volunteered to take part in the experiment (30 males and 30 females; mean/S.D. age: 34.1±10.6). They were recruited from the university campus, were naive with respect to the purpose of the experiment and had normal or corrected-to-normal vision. The studies conformed to the declaration of Helsinki. Among the participants, 19 subjects had never tried VR, 33 had limited experience with VR and 8 had knowledgeable experience with VR. Every participant signed an informed-consent form before the experiment.

5.3.2 Apparatus

The experiment was developed using Unity software (version 2018.2.19f1). Participants were immersed in VR using a HTC Vive PRO Head-Mounted-Display (HMD) and equipped with two Vive controllers (one in each hand) and two Vive trackers (one attached to each foot). There were embodied in a gender-matched avatar that was animated using inverse kinematics (Unity FinalIK plugin) using the positions of the HMD, the controllers and the trackers.

5.3.3 Task & Threat

In order to increase the coherence of a potential threat occurrence, we chose to put participants in a virtual environment that represented a factory where potential incidents might happen, e.g., a malfunction of a dangerous machine (see Figure 5.1, left). More precisely, participants had to perform a task that consisted in grabbing a metallic ingot, putting it on a plate coming on a conveyor lay, then pressing a button so that a crusher smashed the ingot to transform it into a metallic pinion (see Figure 5.6). Before the ingot was placed on the plate, the button remained red, and only if the ingot was correctly placed within rectangular boundaries drawn on the plate, the button would turn green and become pressable. Therefore, participants had to be precise in their gesture.

All the task interactions were performed by participants using their dominant hand. Depending of whether participants were left or right-handed, the environment was mirrored symmetrically, e.g., the box containing the ingots as well as the button were placed on the opposite side. Using the original 3D model of the HTC Vive controller, we attached a 3D magnet on top, which participants used to grab the virtual ingot by pressing the controller trigger. To release the ingot, participants simply released the controller trigger.

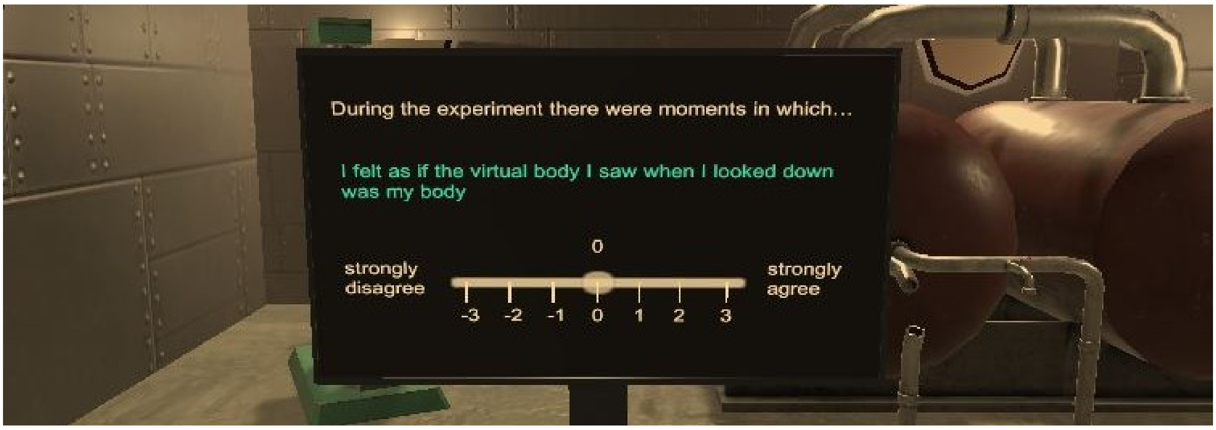
The threat consisted in a malfunction of the crusher, which would suddenly activate while participants were positioning the ingot on the plate (i.e., the participants' hand was still under it). It was accompanied by a threatening sound of a "machine crash", working not only on the visual but also on the auditive dimension. The crusher would go down to the plate, to increase the chances to collide with the virtual arm, by the speed of 2 m/s. The threat was thus designed in a way that would make it plausible for the participants, in order to ensure its efficiency in virtually threatening them. Moreover, a vibration was given through the HTC Vive controller each time the crusher smashed the ingot or malfunctioned.

5.3.4 Experimental Protocol

Upon their arrival, participants read and signed the experiment consent form and filled in a demographic questionnaire (collecting age, gender and experience in video games and VR). They were then briefed about the experiment and equipped with the HMD, controllers and trackers. Afterwards, avatars were re-scaled so that the dimensions matched the participant's eye-height, as well as arm span, which were computed from the position of the HMD and controllers while the participant held a N-pose. Finally, participants were immersed in the virtual environment. They all started the experiment facing a virtual mirror in the virtual factory (see Figure 5.3), giving them the opportunity to see their full virtual body animated by their own motions. When they were ready to start, the mirror disappeared by mechanically sliding towards the ceiling, and the experiment began. From this point, the experimental flow was divided into three blocks that involved 12 trials each. One trial consisted in performing the task once. The overall organization of the experimental flow is summarized in Figure 5.5.

A threat was introduced at the end of the second block (in the 24th trial). The same threat was then introduced again in the third block during trials 26, 30, 33 and 34. A control group of participants was considered for the experiment, for which no threat was ever introduced, meaning that all trials were similar. At the end of each block, participants answered an embodiment questionnaire (an adapted version of González-Franco and Peck's embodiment questionnaire [2018]) while being immersed in the virtual environment. A virtual television appeared in the factory with questions written on it, and participants answered the questions with the trackpad and trigger of their right controller (see figure 5.4). Finally, after the last block, participants were unequipped and answered a final questionnaire which included a presence questionnaire [Usoh et al. 2000]. Each trial lasted approximately 5 seconds and participants performed in total 36 trials each. The

Figure 5.3 – Phase of familiarization with the virtual avatar facing a mirror, captured from a third person point of view (left) and a first person point of view (right).



During the experiment there were moments in which...

I felt as if the virtual body I saw when I looked down was my body

Figure 5.4 – Television displaying the subjective questions asked to participants between blocks.

whole experiment, including welcoming of participants, reading and signing the consent form, and answering questionnaires lasted approximately thirty-five minutes.

5.3.5 Experimental Design

A mixed-design was adopted for the experiment, considering two independent variables: Group and Block. Group was a between-subject factor with two levels (*threat* and *control*), corresponding respectively to half of the participants (n=30: 15 women and 15 men) that encountered a threat during the experiment and the other half of the participants (n=30: 15 women and 15 men) who performed the whole experiment without experiencing a threat. Block was a within-subject factor with three levels corresponding to the blocks of the experiment flow:

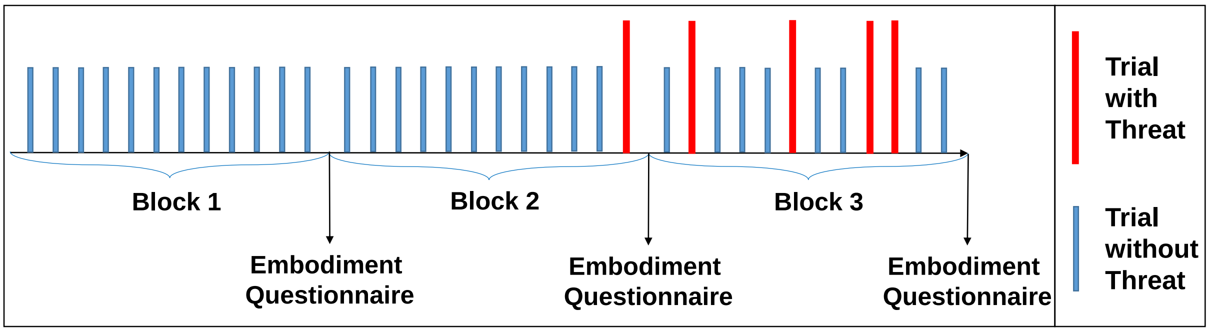


Figure 5.5 – Summary of the experimental design. In *control* group, threat trials were replaced by safe trials without any threat.

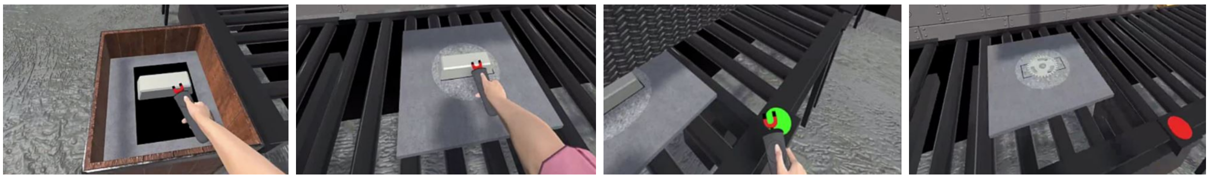


Figure 5.6 – Different steps of the task: grab the ingot (first), place it on the plate (second), press the button (third), the ingot was smashed into a pinion (fourth).

first, *second* and *third*.

Regarding dependent variables, both objective and subjective data were collected during the experiment to assess participants' SoE as well as threat responses.

5.3.5.1 Subjective Data

Each participant answered a subjective embodiment questionnaire at the end of each block, inspired from the questionnaire proposed by González-Franco and Peck [2018]. The questions were divided into four categories (Ownership, Agency, Self-Location and Threat). However, since one group did not encounter any danger, only Ownership, Agency and Self-Location were used to compute SoE scores. For the same reason, threat related questions were only analysed for the group with danger. All the questions were answered on a 7-point Likert scale, from -3 (strongly disagree) to 3 (strongly agree), and can be found in Table 5.1.

In addition, participants answered a final questionnaire at the end of the experiment, which contained an additional presence questionnaire (7-point Likert scale) [Usoh et al. 2000]. As previous work showed that fear in VR could be influenced by the sense of presence [Diemer et al. 2015], and that both immersion and emotional content can also impact the sense of presence [Baños, Botella, Alcañiz, et al. 2004], we thus expected that the way participants would react to the virtual threat would be influenced by how much they believed to be in the virtual factory.

5.3.5.2 Objective Data

In order to assess participants' physical response to the threat, as well as potential changes in their behaviour while performing the task after the threat was introduced and repeated, the motion (position and orientation per frame) of the participants' dominant hand was recorded. In addition, the time during which the dominant hand was under the crusher was also recorded for each trial. To gain some insights regarding the objective reaction to threat during the experiment, speed profiles were computed for each participant and each trial. More precisely, we were interested in the direct physical reaction from participants to the threat stimuli, but also the potential impact on user behaviour while performing the task in the safe trial (a safe trial is a trial with no threat occurrence, independently of the group of participants).

5.3.5.3 Hypotheses

In this experiment, we were interested in evaluating the impact of threat occurrence and its repeatability on the SoE and threat response in VR. Indeed, while the first occurrence of a threat in a VE might elicit a strong fear reaction accentuated by a potential surprise effect, we hypothesized that its repetition would tend to decrease its effect due to the absence of nociceptive feedback and thus credibility.

Regarding the influence of the first threat occurrence, we first hypothesised that it would impact positively the subjective measure of the SoE. Indeed, previous research showed that experiencing emotional response such as fear in a virtual environment leads to a stronger sense of presence [Gromer et al. 2019], another subjective perception of the virtual experience. While, the sense of presence differs from the SoE, previous works showed that they are not likely to be totally independent [González-Franco and Peck 2018]. However, other studies also showed that the stress induced by threats can be detrimental to cognitive functions such as spatial working or memory [Murphy et al. 1996]. More precisely, a study from Christensen et al. [2019] showed that fear induction was detrimental to the sense of agency of users towards their actions. While these studies were not conducted in VR, we may wonder if a virtual threat would impact similarly user cognitive functions and possibly their SoE. Fear was thus both shown to be detrimental to the sense of agency of users towards their actions as well as leading to a stronger sense of presence. Nevertheless, as agency is related to embodiment, we considered that the second hypothesis was more likely to be accepted. For this reason, we argue that the SoE could be negatively impacted by the first occurrence of the threat, i.e., that participants would experience a lower SoE after experiencing a threat. We also hypothesised that this first threat occurrence would have an impact on participants behaviour while performing the task afterwards, because of the anxiety being raised by the threat. More precisely, we believed those changes would be visible either by a accelerated speed while doing the task or a decreased time of their dominant hand spent under the crusher. However, when considering the repeatability of the threat introduction, the expected the impact on the SoE and Threat response to be different. Indeed, when experiencing a virtual threat in VE, participants encounter visual feedback as well as sometimes auditory or tactile feedback. However, no nociceptive feedback is associated with the virtual threat, which might at some point break the illusion. Hence, because we expected the repetition of the threat to decrease its efficiency in making participants react, we supposed their physical reaction to it would decrease along the repetitions and that their subjective response to the threat (answers to subjective questions about how the threat was perceived) would also be diminished. In addition, we expected the loss of plausibility of the virtual threat to impact negatively the SoE, e.g., that if participants lost conviction of the VE they might also loose conviction of their virtual body. Finally, we expected that these effects would not be present in the control group and therefore not related to the exposure time.

In summary, considering our experimental design, our main hypotheses are as follows.

H1: In the *threat* group, the SoE scores will be lower after the first threat (i.e, lower after the *second* block than after the *first* block.)

H2: In the *threat* group, the SoE scores will be lower after several repetitions of the threat (i.e, lower after the *third* block than after the *second* block as well as than after the *first* block.)

H3 (control): In the *control* group, the SoE scores will remain similar between all blocks.

H4: In the *threat* group, the scores of subjective threat responses (Threat category of subjective embodiment questionnaire) will be lower in the *third* block than in the *second* one.

H5: In the *threat* group, the physical response to the threat will decrease along the repetitions of the *third* block.

5.4 Results

Mixed two-way ANOVA analyses were performed when comparing scores of SoE between the blocks (within-subjects) and the two groups (between-subjects). The normality assumption was tested using Shapiro-Wilk test and when not verified, an Aligned Rank Transformation (ART) was applied on the data. Tukey's post-hoc tests ($\alpha = .05$) were conducted to check

Table 5.1 – Questionnaire used in the experiment. Questions in italics are control questions.

Variable	Question
Ownership	O_1) I felt as if the virtual body I saw when I looked down was my body. O_2) *It felt as if the virtual body I saw was someone else.* O_3) *It seemed as if I might have more than one body.*
Agency	A_1) It felt like I could control the virtual body as if it was my own body. A_2) The movements of the virtual body were caused by my movements. A_3) I felt as if the movements of the virtual body were influencing my own movements. A_4) *I felt as if the virtual body was moving by itself.*
Self-Location	SL_1) I felt as if my body was located where I saw the virtual body. SL_2) *I felt out of my body.* SL_3)I felt as if my (real) body were drifting towards the virtual body or as if the virtual body were drifting towards my (real) body.
Threat	T_1) I felt that my own body could be affected by the crusher. T_2) I felt a fear sensation in my body when the crusher malfunctioned, if it did. T_3) When the crusher malfunctioned, if it did, I felt the instinct to move my hand. T_4) I had the feeling that I might be harmed by the crusher.

significance for pairwise comparisons. When comparing scores of threat subjective questions, Friedman test was performed between blocks as normality assumption was not verified. As for correlation analyses, Pearson's r (r) was used for parametric data and Spearman's r (r_s) was used for non-parametric data.

5.4.1 Subjective measure of the Sense of Embodiment

The embodiment scores were computed by averaging the scores of Ownership, Agency and Self-Location. As previously said in Section 5.3, Threat scores were not included in the SoE computation since one group did not encounter any threat. A mixed-two way ANOVA (group, block) analysis was performed on embodiment scores as well as on each sub-component. We did not find significant differences between the embodiment scores depending on the block or the group, or their interaction, which thus does not support **H1** nor **H2**. The general mean score are 1.77±0.67 (S.D.) for embodiment, 1.12±1.16 (S.D.) for ownership, 2.30±0.58 (S.D.) for agency and 1.87±0.91 (S.D.) for self-location.

Although not significant, the here-above analysis highlighted a tendency for Ownership scores to decrease from block 1 to block 3. We thus decided to perform a mixed-two way

ANOVA (group, block) analysis on each question of ownership independently, which highlighted a significant order effect for O_1 and O_3 from Ownership questions ([$F_{2,116}$=4.26, $p < .05$] for O_1 and [$F_{2,116}$=8.55, $p < .001$] for O_3). Post-hoc tests showed that O_1 scores were significantly lower in block 2 than in block 1 (p<.05) and that O_3 scores were higher in block 2 that in block 1 (p<.05) and higher in block 3 that in block 1 (p<.001). These results suggest that the repetition of the experimental blocks had an negative impact on some questions related to subjective Ownership, independently of whether a threat was introduced or not during the experiment, which does not allow the validation of **H3**.

5.4.2 Subjective Response to Threat

Subjective responses to the threat were analysed in two groups: Event Related questions (**ER**) refers to the two questions directly related to the occurrence of a threat (T_2 and T_3), and Non Event Related questions (**NER**) refers to the questions related to general fear towards the crusher (T_1 and T_4). Friedman tests were performed to analyse responses to **ER** questions only in the *threat* group, as no threat was introduced in the *safe* group. Significant differences depending on block were found for each question (T_2: χ^2=34.7, $p < .0001$, T_3: χ^2=42.0, $p < .0001$). Wilcoxon tests were thus conducted and showed that threat scores were significantly lower in the *first* compared to the *second* block for all four questions (p<.0001) and in *first* compared to third *third* block (p<.0001). However, no significant difference was found between blocks *second* and *third* (see Figure 5.7). Subjective **ER** threat response thus increases after a first threat occurrence, but does not further increase nor diminishes after several repetitions.

NER questions were analysed for both groups, and a mixed-two way ANOVA analysis was also performed on both questions independently. For both questions, significant effects of group ([$F_{2,58}$=19.37, $p < .001$] for T_1 and [$F_{2,58}$=14.03, $p < .001$] for T_4), block([$F_{2,116}$=5.41, $p < .01$] for T_1 and [$F_{2,116}$=20.22, $p < .001$] for T_4) and interaction between the two ([$F_{2,116}$=11.49, $p < .001$] for T_1 and [$F_{2,116}$=8.56, $p < .001$] for T_4) were found. For T_1 and T_4, post-hoc tests showed that ratings in the *second* and *third* blocks were higher than in the *first* block (p<.0001) for group *threat*, but not for *safe* group (see Figure 5.8). Similarly to **ER** response, these results suggest that subjective **NER** threat response increases after a first threat occurrence, but does not further increase nor diminishes after several repetitions. Hence, these results do not support **H4**.

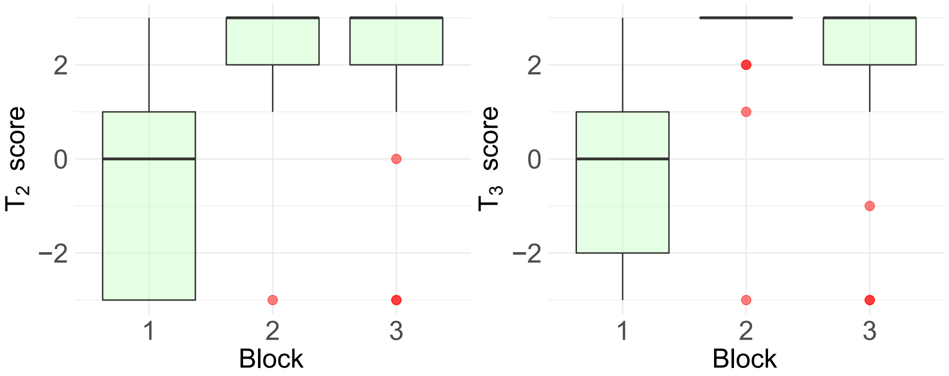


Figure 5.7 – Mean scores of ER threat subjective questions for the *threat* group.

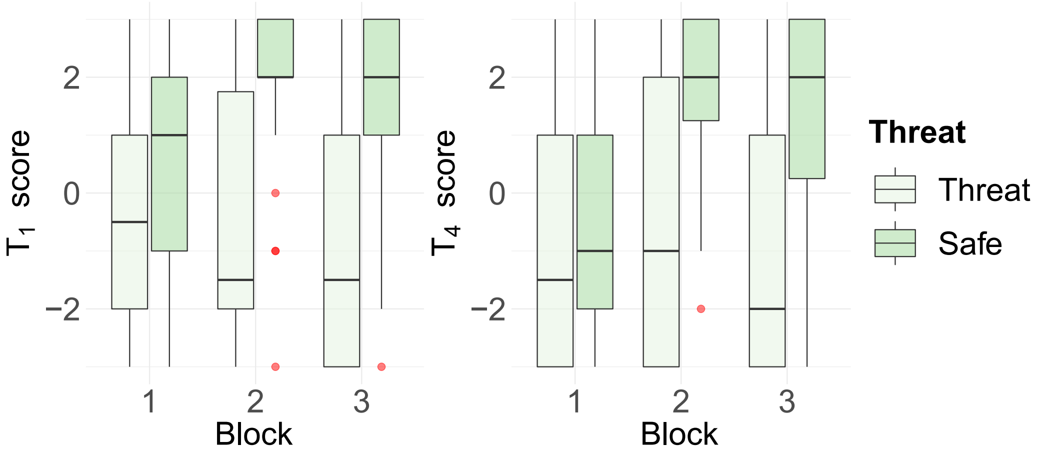


Figure 5.8 – Mean scores of NER threat subjective questions.

5.4.3 Objective Response to Threat

In this analysis, we were interested in comparing objective data depending on trials to search for potential evolution in user behaviour due to threat introduction and repetitions. We thus considered Trial as another independent variable.

5.4.3.1 Time of the dominant hand being under the crusher

We were interested in the time the participant's dominant hand spent under the crusher during each trial (see Figure 5.10), as an information of how “scared” they might be of their hand being potentially crushed while doing the task. More precisely, we were interested in all the safe trials (in which no threat was introduced) ranging from the last safe trial before a first threat was introduced to the last safe trial of the experiment (23, 25, 27, 28, 29, 31, 32, 35 and 36). Five outlier samples were removed for this analysis due to abnormal time values in a few trials,

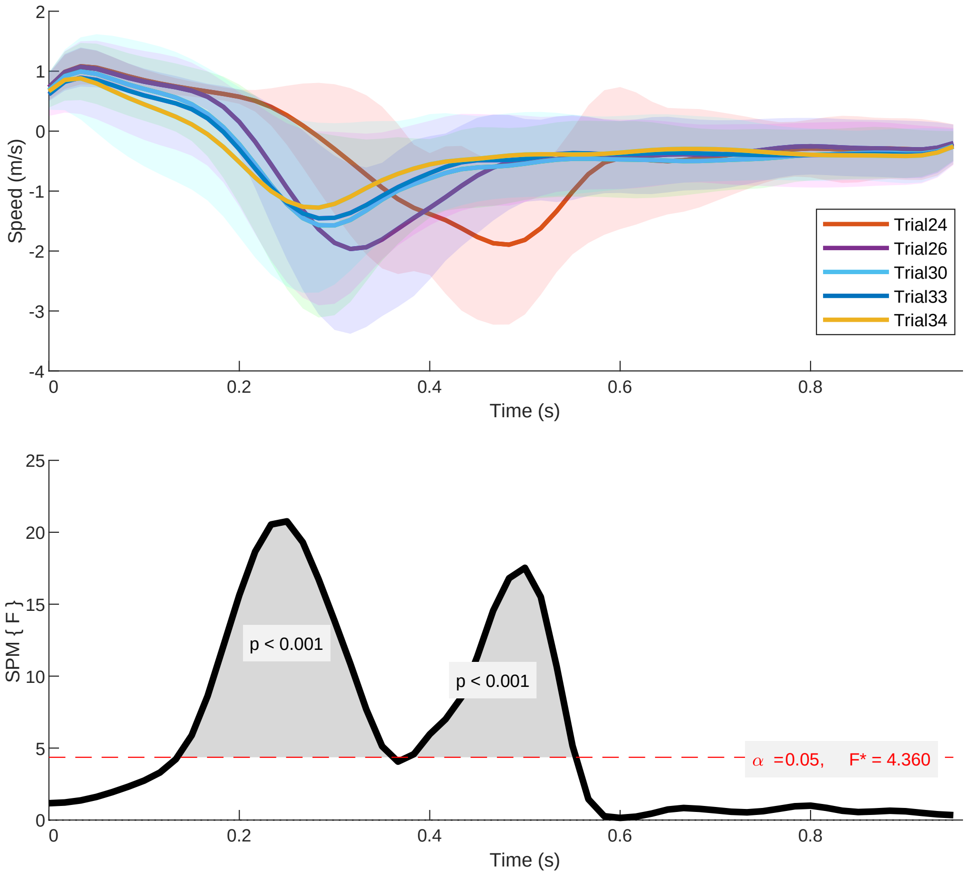


Figure 5.9 – Averaged speed profiles of participants during threat trials (up) and SPM analysis highlighting significant differences between trials (down).

corresponding to a time of either 0s (rare cases in which participants threw the ingot and had it placed perfectly on the plate) or an excessively abnormal time under the crusher (in some situations where participants were scared of the crusher and had to make several attempts to place correctly the ingot under the plate).

A one-way ANOVA was performed on the data from the *threat* group to investigate differences of time among the selected safe trials, and highlighted a significant effect ($[F_{8,232}=4.05$, $p < .0001]$). Post-hoc tests only showed significant effects between trial 23 and all other trials, except 25: the time that the dominant hand spent under the crusher was not significantly lower in the trial following the first threat (25), compared to the trial preceding it (23), but the time in the other safe trials were all significantly lower than trial 23 ($p<.05$). A one-way ANOVA was also performed in *control* group and did not show any significant differences between the investigated trials ($[F_{8,232}=0.53$, $p = .83]$). This result suggests that after the threat was introduced

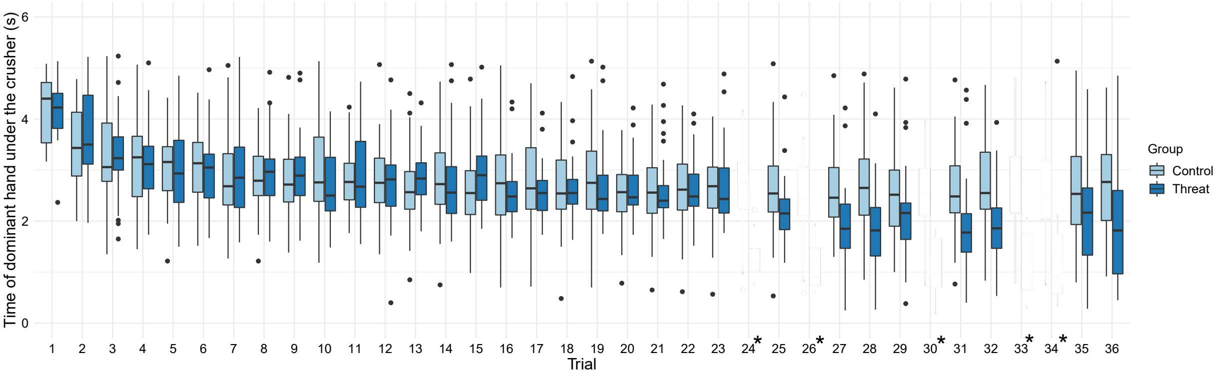


Figure 5.10 – Mean time of dominant hand spent under the crusher per trial for each group. Trials with an asterisk correspond to the trials in which a threat was introduced, and are therefore masked for that the time spent under the crusher in those trials is not comparable with other trials.

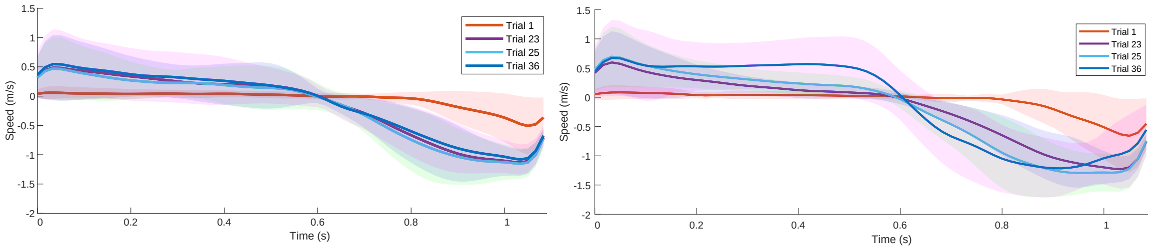


Figure 5.11 – Averaged speed profiles of participants during selected safe trials in the control group (left) and the threat group (right). The sign of the y-axis represents the direction of the motion, positive speeds represent the user moving his hand forward to place the ingot and negative speeds repents the user moving his hand away from the crusher.

twice, participants left their hand a shorter amount of time under the crusher, and thus performed the task faster. The fact that this change of behaviour is not visible in the control group also suggests that this change is due to participants' reaction to the threat.

5.4.3.2 Speed Profiles

For each trial, the speed profiles of the dominant hand while performing the task were computed for each participant, then averaged across participants. More precisely, for the trials in which a threat occurred, the speed profiles were computed from the time the threat occurred and for the trials with no threat, the speed data were aligned between participants on the time the virtual ingot was released from the dominant hand. Data were then cropped in order to ensure having the same length of data for each participant (for trials with a threat, we kept the 80 frames following the frame of the threat introduction, and for safe trials we cropped from 50 frames before the ingot was released to 50 frames afterwards). In addition, to include information about the direction of the hand movement in the analysis, we considered speed values of movements away from the participant (along the X axis, i,e., towards the machine) to be positive, while speed values of movements towards the participant (along the -X axis, i,e., away from the machine) to be negative. This representation enabled us to observe simultaneously the magnitude of the movement of participant's dominant hand, as well as its direction (see Figure 5.9). To analyse the speed profiles, we resampled them at a frequency of 60 Hz, then we filtered the data with a butterworth low-pass filter with a cutoff frequency of 30 Hz to reduce the noise. We evaluated the effect of Trial on the speed profiles using Statistical Parametric Mapping (SPM) methods [Friston et al. 2007]. This process allows comparing time series data taking into account their variability at each time frame.

5.4.3.2.1 Motion data in threat trials: We used SPM analysis to compare speed profiles of threat trials (Trial = 24, 26, 30, 33 and 34) in the *threat* group, which showed a significant effect of Trial ($p<.001$). Post-hoc tests revealed a significant difference between trial 24 (first threat introduction) and all other trials (26, 30, 33 and 34) ($p<.05$). Qualitatively, we can notice that the maximum speed remains comparable among trial 24 and the others, while displaying a temporal shift: on trial 24, participants reacted significantly slower to the threat than in the other trials (see Figure 5.9).

5.4.3.2.2 Motion data in safe trials: We used SPM analysis to compare speed profiles of specific safe trials in both *threat* and *control* groups. More precisely, since we were interested on the impact of threat repetitions on behaviour in safe trials, we compared the first trial (1), the trial before the first threat (23), the trial after the first threat (25) and the last trial (36). SPM analysis showed a significant effect of Trial on speed profiles ($p<.001$) in both groups, on two distinct phases: the forward motion of the dominant hand, and the backward motion. In the *threat* group, post-hoc tests showed significant differences between the last trial of the experiment and trials 23 and 26, yet only in the forward motion ($p<.05$) (see Figure 5.11). This result shows that in average the approaching speed was higher for the *threat* group for the last trial. Regarding the *control* group, SPM analysis only showed a significant difference between the firts trial and the other safe trials. Overall, those results do not support **H5**, as the repetition of threats did not impact physical threat response.

5.4.4 Presence and Threat

From the final questionnaire we computed the mean scores for presence regarding the global experiment for each group (*threat*, *control*). While presence questionnaires were only collected at the end of the experiment and thus could not show the impact of threat introduction and repetitions on presence, it enabled us to compare presence score between our two groups of participants. Presence scores were relatively high and were similar for both groups (5.24±1.09 (S.D.) for *threat* and 5.08±1.11 (S.D.) for *control*). They were also not statistically different after performing a Mann-Whitney test (p=.21), showing that the sense of presence was not significantly different between the group that encountered several threat introductions and the control group.

5.5 Discussion

The main objective of this study was to investigate the potential impact of threat occurrence and repetition on users' SoE and threat response. More precisely, we hypothesised that a single threat occurrence would increase participants' SoE towards their avatar, but that threat repetition would tend to decrease it. In addition, we expected threat repetition to cause a decrease in participants response to threat. In this section, we discuss our results regarding the influence of threat occurrence and repetition on threat response and the SoE. Finally, we discuss the potential impact of threat on participants' behaviour as well as the link between presence and threat.

5.5.1 Threat Responses

Subjective and objective data of threat response were collected for two main reasons. First, we wanted to verify that participants reacted to the threat we had designed, which was validated by both the subjective and behavioral responses. Participants from the *threat* group significantly reacted to the threat introduction by a fast withdrawal of their hand, visible in the results by a significant speed peak of their dominant hand when the threat occurred (Figure 5.9). They also rated a strong subjective feeling of fear towards the crusher when it malfunctioned (Figures 5.7 and 5.8). Second, we were interested in the impact of threat repetition on the way it was perceived by participants. We indeed had the hypothesis that the repetition of the threat would impact its credibility due to the absence of nociceptive feedback, and that in consequence participants would loose faith in it and stop reacting. However, this was not observed in our results. The subjective ratings regarding the fear induced by the threat were in the third block as high as the ratings in the second block, which did not support **H4**. Regarding the objective data, speed profiles only highlighted a difference between participants speed profiles in the first threat introduction and all the other threat occurrences. More precisely, the average speed peak remained similar for all threat trials (around 2m/s), but the peak was shifted: the first time the threat occurred, participants took more time to react to the threat than in the other threat trials. While we would have expected the speed peak to decrease along the repetitions of threat, we can notice in Figure 5.9 that although not significant, the speed peak tends to diminish in the last threat trials (30, 33 and 34). Although some adaptation is observed along the experiment, the current results do not support that the repetition of a threat alters physical threat response (**H5**). Nevertheless, we may wonder whether the number of threat repetitions was sufficient, which is why we address this matter in Section 5.5.4.

As we can see in Figure 5.11, our results also highlighted changes in user behaviours in the safe trials that occurred after the threat occurrences. Before the ingot was released ($t \approx 0.6s$), we can observe that the approaching speed increased in both groups. Yet, we can observe that this effect is higher, and significant, in the last trial of the danger group. By increasing the approaching speed, participants seem to have tried to avoid "more" the threat after several threat occurrences. Yet, interestingly the subjective data does not support an increased fear towards the crusher by the end of the experiment. This result is also coherent with results regarding the time that the dominant hand stayed under the crusher.

5.5.2 Threat Occurrences and Sense of Embodiment

The results regarding the subjective measure of the SoE did not show any impact of the threat first occurrence nor of its repetition, which thus does not fulfill our hypotheses (**H1** and **H2**). According to the work of Christensen et al. [2019], we expected the fear induced by the crusher malfunctioning to negatively impact the sense of agency of participants. Christensen et al. have indeed shown that fear expectation alters users' sense of agency. Their study was inspired from the work of LeDoux [2003], which states that fear is associated with automated behavioural patterns. Indeed, fear commonly induces automatic withdrawal responses or action inhibition (e.g., fleeing or freezing) [Christensen et al. 2019]. We indeed observed such patterns in the participants' response to the crusher malfunction, as visible for instance in Figure 5.9, which highlights a speed peak when participants moved their hand backward from the machine after a threat was introduced. However, while Christensen et al. found an impact on users' sense of agency, no impact was found in our study on users' sense of agency towards their avatar, nor over their SoE. Nevertheless, we must emphasize two main differences between the study of

Christensen et al. and our study. First, their study was not conducted in virtual reality, and the sense of agency thus did not refer to the control of a virtual avatar. Moreover, in their study they specifically informed participants that in some blocks of trials, no threat would ever be introduced, and that in other blocks one or several threats might occur. Participants were thus perfectly aware of when they were to expect a threat or feel safe. In our implementation, this was not transparent for participants. In the consent form participants signed, they were briefed that a "malfunction of the crusher" could occur, with no more precision. We must consider that, entering the experiment, participants might have been in a "threat expectation" state. It would thus be interesting to replicate this study being transparent with participants on when a threat could occur or not, e.g., to measure whether we are able to replicate Christensen et al.'s results.

Moreover, our threat was designed as in most embodiment studies [González-Franco, Peck, et al. 2014; Zhang, Ma, et al. 2015], in a way that it would visually affect the integrity of the virtual body by colliding with it. After verification in the analysis, we found that over 150 trials with a threat, the crusher collided 128 times with the dominant hand of participants (mean/S.D. time of collision in seconds: 0.21 ± 0.10). Other times, participants might have withdrawn their hand too fast, but in all cases participants experienced a vibration on the controller when the threat happened. This vibration was important as it is a common fact that mismatches between what you see (e.g. an object touching your avatar) and what you feel (e.g. tactile feedback) decrease the SoE towards the avatar [Kilteni, Groten, et al. 2012]. However, we must acknowledge that the coherence between visual input and tactile feedback differs within experiences. For instance, the coherence between visual and tactile is not the same whether the participants' hand is virtually brushed while being brushed simultaneously in the physical world [Hoyet et al. 2016], or if the participants' hand is virtually harmed by a knife while receiving a vibration in the physical world [Ma and Hommel 2013]. The notion of coherence in virtual environments has been shown to be of great importance to have participants react realistically to the virtual environment [Slater 2009]. In our experiment, no nociceptive feedback was associated with the virtual threat. For this reason, we expected this lack of coherency to negatively impact threat response along the threat repetitions (**H5**). However, even though participants noticed and reacted to the threat, the quickness of the threat in our experiment might have prevented participants from observing the actual collision, which could be a possible reason why we did not observe a decrease of the physical response to the threat in the last block. It would thus be very interesting in future work to investigate the potential impact of mismatch between tactile feedback and virtual threat on the SoE.

Our results also highlighted a sequential effect of the repetition of the blocks on two questions regarding ownership, which was also present in the control group and therefore did not allow the full validation of **H3**. However, it remains unclear weather the scores were impacted by the duration of the experiment (i.e., the duration would then impact negatively the illusion of ownership), or by the repetition of questionnaires regarding the sense of embodiment (i.e., answering the questions may lead to an increased attention given to the virtual body, which may put in evidence artefacts that would affect the illusion).

5.5.3 Presence and Threat

Presence has an interesting bidirectional relation with anxiety and emotional state as the sense of presence was shown to be increased by affective content [Gromer et al. 2019; Baños, Botella, Alcañiz, et al. 2004], but also to influence the perception of fear in VR [Diemer et al. 2015]. Nevertheless, our results did not highlight such impacts, while we must acknowledge that we only compared between threat and control groups presence scores that were gathered at the end of the experiment. While this was not the main focus of this paper, we believe it would be interesting to deeper investigate in future studies the relation between affective content and the sense of presence in VR.

5.5.4 Limitations

When designing our experiment, a number of choices were made regarding the implementation of the threat. As presented in Section 5.2.2, there exist many different kinds of threats in the literature in embodiment studies. We decided to make coherence the main aspect of our threat, placing it in a realistic context where an accident is likely to happen. In addition, our threat was associated with auditory and tactile feedback and was conceived to collide with the virtual body. All those choices made in the experiment can potentially bias the results, and therefore, it would be interesting to validate that our results generalize to other threats, or at least to similar types of threats. For instance, while we expected participants to be conscious of the collision of the threat with their virtual body, we believe that replicating this experiment with a threat that makes the collision more obvious would be interesting.

Furthermore, the length of the experiment could have also played a role in the results. Indeed, although not significant, we observed adaptation patterns that appeared in the motion profiles. In the experiment, we decided to keep a low number of threat repetitions, as done in most experiments on embodiment, and to reduce fatigue. Nevertheless, changes in the physical reactions of the participants might become more obvious with a longer exposure, and it remains unclear if these changes would remain between VR sessions.

5.6 Conclusion

In this chapter, we explored the potential impact of threat occurrence and repeatability on users' Sense of Embodiment (SoE) and threat response. The main results show that the introduction of a threat does not alter users' SoE but might change their behaviour while performing a task after the threat occurrence. In addition, threat repetitions did not show any effect on users' subjective SoE, or subjective and objective responses to threat. Furthermore, it seems that the changes on physical responses to threat are modulated by threat repetitions, although the results are not always significant. We may therefore consider that there is an adaptation associated with threat repetition, and that it remains unclear if this adaptation would continue if the experiment would last longer. Taken together, our results suggest that embodiment studies should expect potential changes in participants behaviour while doing a task after a threat was introduced, but that threat introduction and repetition do not seem to impact the subjective measure of the SoE (user responses to questionnaires) nor the objective measure of the SoE (behavioural responses to threat towards the virtual body).

This chapter bring the first part of this thesis to a close, after exploring the impact of the VE on the SoE through three different angles:

- First, we showed that sharing the VE with other users has no impact on users SoE, but influences their engagement towards the task.
- Second, we introduced the concept of virtual co-embodiment and showed how sharing the control of an avatar modulates users' own SoA towards it.
- Third, we highlighted that threat introduction does not influence nor negatively or positively the SoE, but that threat repetition seems to modulate threat responses from participants.

In the second part of the manuscript, we go one layer deeper in our representation of factors (Figure 8.5), by focusing on the factors related to the avatar itself. More precisely, in the following chapter, we are interested in three important factors of the SoE (appearance, control and PoV towards an avatar), and investigate their relative preference by users.

PART II

Users relative preference within factors influencing the Sense of Embodiment

"We are our choices."

Jean-Paul Sartre

6

Studying the Relative Preference Between Appearance, Control and Point of View

Abstract:

In Virtual Reality, a number of studies have been conducted to assess the influence of avatar appearance, avatar control and user point of view on the Sense of Embodiment (SoE) towards a virtual avatar. However, such studies tend to explore each factor in isolation. This chapter aims to better understand the inter-relations among these three factors by relying on a methodology called subjective matching technique, which has never been used for studies on the SoE. In the presented experiment (n=40), participants had to match a given "optimal" SoE avatar configuration (realistic avatar, full-body motion capture, first-person point of view), starting by a "minimal" SoE configuration (minimal avatar, no control, third-person point of view), by iteratively increasing the level of each factor. The choices of the participants provide insights about their preferences and perception over the three factors considered.

Figure 6.1 – The four tasks implemented in the subjective matching experiment with the avatar's appearance at maximum level of realism. From left to right: *Punching*, *Soccer*, *Fitness* and *Walking*.

6.1 Introduction

In the past years, several studies highlighted different "factors of influence" towards the subcomponents of the SoE, e.g., the avatar's appearance [Argelaguet et al. 2016] or the user's point of view [Gorisse, Christmann, Amato, et al. 2017]. However, despite the worthwhile insights brought by these studies, the inter-relations between the factors influencing the SoE remain uncertain. Kokkinara and Slater [2014] had explored the relative importance of visuomotor and visuotactile synchronous stimulation on the sense of ownership that they mesured by recording "breaks in the illusion of ownership". Yet, if we start to better understand the influence of isolated factors on the SoE, we still have little information regarding the relative contribution of each factor towards the SoE, or regarding the user's preference for a factor over another while being embodied in an avatar. As for today, several questions remain open: Is there a dominant contribution between the factors of influence towards the SoE? Should some of these factors be prioritized in the creation of virtual avatars?

In order to provide insights to these questions, we present two experiments exploring user preference and perception of three factors commonly found in the literature to influence the sense of embodiment, namely the avatar's visual appearance, the avatar's control, and the user point of view. In Chapter 2, we presented how these factors could be divided in different levels, and how different characteristics of each could influence the subcomponents of the SoE. The first experiment (baseline experiment, n=20) had the objective to create an ordered list for the levels within each factor (e.g., ranking between the different degrees of realism for an avatar appearance, ranging from abstract to personalised avatars). For each factor, participants experienced all levels while performing a task and had to rank their preference for each level on a scale from 0 to 100. The task consisted in recreating a yoga posture in front of a mirror.

The second experiment (n=40) used the results obtained in the baseline experiment in order to explore through a subjective matching technique how participants combined them to reach a given level of SoE. Subjective matching experiments have already been successfully conducted on the factors impacting Place Illusion and Plausibility Illusion in VEs [Slater, Spanlang, and Corominas 2010; Skarbez et al. 2017]. Such experiments aim at studying qualia, i.e. qualities or properties as perceived or experienced by a person such as the Place Illusion, the Plausibility illusion or what interests us in this study, the Sense of Embodiment, avoiding the use of subjective questionnaires or purely physiological and behavioral measures. More precisely, in our case the experiment consisted in having participants experiencing an "optimal" configuration of an avatar and then "recreate" the experienced SoE by iteratively increasing, one level at a time, one factor, starting from a "minimal" configuration. The final matched configuration, named accepted configuration, should match the same SoE experienced with the "optimal" configuration. The initial "optimal" configuration was supposed to elicit a high SoE as it considered a partially customized avatar, full-body motion capture and a first-person point of view, while the "minimal" configuration consisted in a minimal avatar, with automatic animations and a third-person point of view. These configurations were defined according to ranking results from the baseline experiment. The choices of the participants provide insights about their preferences and perception over the three factors. In addition, to assess the potential impact of users actions while being embodied in an avatar, the subjective matching experiment considered four different tasks which covered four actions that can be done in a virtual environment: a) an interaction with the upper-body, b) an interaction with the lower-body, c) mimicking the actions of another virtual character full-body motions, or d) a constrained walking task. We had three main hypotheses. First, that we could create a monotonic ranking for the different levels of each factor. Second, that some factors would be prioritized over other factors. Finally, we expected the task to have an impact on the results.

6.2 Overview and General Experimental Details

The main objective of this experiment was to identify potential preferences within factors of influence towards the SoE. To do so, we first conducted a baseline experiment to define the number and order of the different levels for each factor of influence towards the SoE. We then conducted a subjective matching experiment, similarly to the studies on Presence of Slater et al. [2010] and Skarbez et al. [2017], in order to better understand the inter-relations between these factors. In this section, we detail the subjective matching technique used in our main experiment as well as the experimental details common to both experiments.

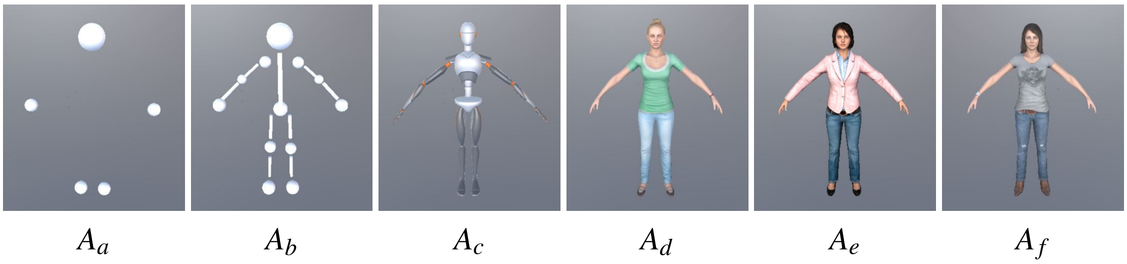


Figure 6.2 – Levels of the *Appearance* factor. From left to right: (A_a) Abstract avatar, (A_b) Stickman, (A_c) Dummy avatar, (A_d) Opposite realistic avatar, (A_e) Neutral realistic avatar and (A_f) Personalized realistic avatar.

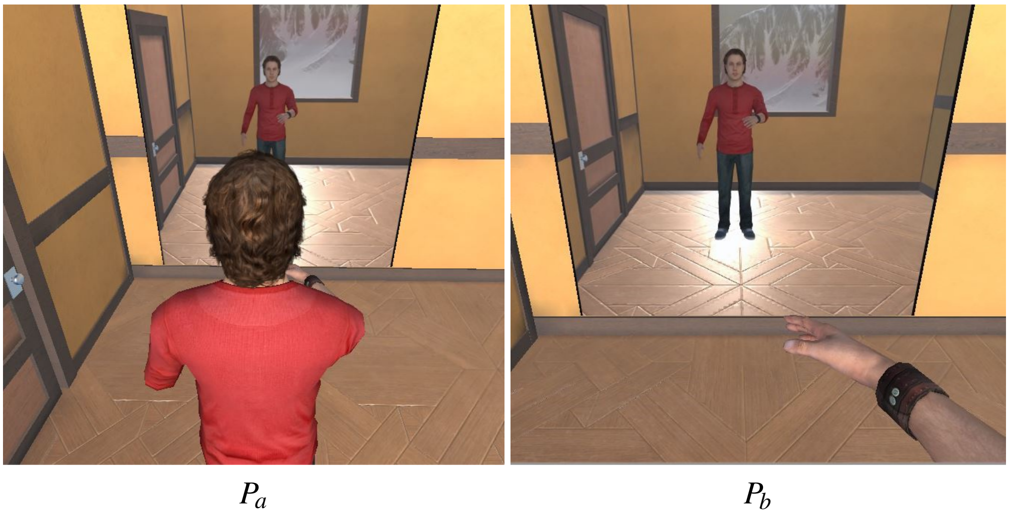


Figure 6.3 – The two levels of the *Point of View* factor: (P_a) Third-person PoV, (P_b) First-person PoV

6.2.1 Subjective Matching Technique

The subjective matching technique is a method commonly used in color science where a particular color sensation is considered as an equivalence class over a number of different wavelength distributions. Typically, users are presented with a color, then asked to reproduce the same color by additively mixing the three primary colors.

In the context of this study, a particular SoE could similarly be considered as an equivalence class over different levels of factors that may influence it, and users were therefore asked to reproduce a given SoE by combining different levels of these factors. A combination of several levels of factors is called hereafter "configuration". In our case, these factors are the Appearance, Control and Point of View, leading to numerous possible avatar configurations with many potential degrees of SoE. Moreover, the SoE felt in a specific configuration combining the three factors might by be equivalent to one felt in another configuration of these factors. The subjective matching technique used in the experiment therefore involves users trying a specific “optimal” configuration of avatar, and remembering their SoE in this configuration. They are then asked afterwards to combine several levels of factors to match again the SoE felt in the initial configuration. More precisely, to each factor is associated a number of levels of improvement, assuming that having all the factors at their maximum level would lead to the best configuration in which users are more likely to have the highest SoE. This method therefore enables to highlight a) which factors participants are more likely to improve and in which order, and b) which configurations will elicit a SoE equivalent to the one felt in the best configuration.

6.2.2 Factors and Levels

To do such an experiment, we chose to focus on three factors (independent variables), with the objective of covering as much as possible the different degrees of SoE likely to be felt towards an avatar. The visual *Appearance* of the avatar was chosen to encompass visual feedback of the avatar that relates to graphical features. The *Control* was chosen to embrace any capabilities of having the avatar animated in the VE. Finally, the *Point of View* was chosen to include different perspectives taken from a user towards the virtual body of the avatar. For each factor several levels were identified with an initial pre-supposed ranking which was refined in a baseline experiment (see Section 6.3). The main requirements for choosing the factors and levels were to ensure good coverage of potential implementations of an avatar according to each factor, as well as allowing the combination of levels between factors. For instance, we did not separate *Appearance* into texture and shape as realistic textures would hardly be combinable with abstract geometrical representations. Similarly, we did not include finger animation since it could not consistently be combined with all the appearance levels. These implications are discussed in more details in Section 6.6.

6.2.2.1 Appearance

The appearance of an avatar can be addressed over several characteristics: the general structure of the virtual body, the shape and dimension of body parts, the render style, etc. Those characteristics combined together contribute to different levels of avatar realism, anthropomorphism and fidelity towards the user. As detailed in Chapter 2, many visual configurations of avatars have been tested in order to evaluate their influence on the SoE and more precisely on its subcomponents. For our experiment, we have selected 6 levels that we believed were the most represented in past studies (see Figure 6.2), ranging from low to high realism and anthropomorphism representations (including the distinction of three realistic avatars in terms of fidelity):

- (A_a) Abstract avatar. Only extremities of the body are visually represented with white spheres.
- (A_b) Stickman. Extremities and main body joints are visually represented with white spheres and cylinders.
- (A_c) Dummy avatar. An avatar with a human body shape but a robotic appearance.
- (A_d) Opposite realistic avatar. A realistic gender-matched humanoid avatar that participants chose among a list of 20 different avatars (20M, 20F) with the instruction of choosing one that they considered to be their opposite in terms of resemblance.
- (A_e) Neutral realistic avatar. A realistic gender-matched humanoid avatar that participants chose among a list of 20 different avatars (20M, 20F) with the instruction of choosing one that did not evoke them anything particular.
- (A_f) Personalized realistic avatar. A realistic gender-matched humanoid avatar that participants chose among a list of 20 different avatars (20M, 20F) with the instruction of choosing one that they considered to resemble them the most. This avatar could then be slightly personalized in terms of hair, eye and clothes color.

6.2.2.2 Control

Similarly, we selected four levels of Control based on previous works, that we believed were most likely to have different effects on the SoE.

- (C_a) Automatic animation. When participants enter a specific zone in order to perform the task, an animation is automatically launched on the virtual body which makes the avatar do the task while the participants actually have no control over it.
- (C_b) Triggered animation. Pressing a button, participants can trigger themself the animation performing a task in the VE (same animation as in C_a).
- (C_c) Inverse Kinematics. The virtual body is animated using Inverse Kinematics, enabling the animation of the avatar from participants' head, hands and feet positions and orientations.
- (C_d) Motion capture. The virtual body of the avatar is animated using a motion capture system (Xsens system).

6.2.2.3 Point of View

Two levels were chosen for the PoV depending on participants perspective towards the virtual body (see Figure 6.3).

— (P_a) Third-person PoV. Users see their virtual body from a classical over-the-shoulder PoV, as commonly used in video games.

— (P_b) First-person PoV. Users see their virtual body as if they were in the avatar's head (as they would see their own body in real life).

6.2.3 Apparatus

For both experiments, the virtual environment was developed in Unity (version 2018.3.14f1) and displayed using an HTC Vive PRO HMD. For head tracking, the internal tracking of the HTC Vive HMD was used. For body tracking, participants wore an IMU-based (Inertial Measurement Unit) motion capture system (Xsens). IMU sensors were equipped on the participants using motion capture suit and straps. The body tracking was handled by the Xsens MVN Animate software platform and streamed to Unity in real time. When using Inverse Kinematics, the FinalIK plugin was used to animate the avatar by following the feet, hand and pelvis positions provided by the Xsens software. Participants also held Vive Controllers in their hands to interact with the virtual environment.

6.2.4 Participants

Twenty participants took part in the baseline experiment (17 males and 3 females; mean/S.D. age: 25.8±5.6). Forty participants (20 males, 20 females; mean/S.D. age: 32.5±10.1), different than from the baseline experiment, were recruited for the subjective matching experiment. For both experiments, participants were recruited from the university campus, were naive with respect to the purpose of the experiment and had normal or corrected-to-normal vision. The studies conformed to the declaration of Helsinki.

Before each experiment, participants were first briefed about the experiment, signed an informed-consent form and completed a demographic questionnaire. After this process, they were equipped with the Xsens motion capture system before undergoing a calibration procedure that would ensure the efficiency of the motion capture system but also allow to resize the avatar to participants' dimensions. Finally they were equipped with the HTC Vive PRO HMD and started the experiment.

6.3 Baseline Experiment

While previous work findings enabled us to pre-select and pre-rank several levels for each factor, little is actually known about the relative differences between all these levels in terms of their influence on the SoE. For instance, does a stickman actually elicit a significantly lower SoE compared to a dummy character? Or do animations driven by Inverse Kinematics elicit similar or lower levels of embodiment than animations driven by a motion capture system? To better measure these differences, and therefore provide significant levels of improvements between levels in the following subjective matching experiment, we decided to conduct a baseline experiment to accurately define the number and order of the different levels based on user preferences.

6.3.1 Experimental Protocol

The experiment consisted in making participants try and rate all the levels of each factor on a score between 0 and 100. To that aim, participants were immersed in a virtual environment representing a fitness room, facing a mirror and had to perform a task while testing all the levels of each factor. The task consisted in performing an easy yoga pose in the context of a "virtual yoga class" (see Figure 6.4, left). More precisely, a specific zone in front of the mirror was highlighted by a luminous disc on the ground, and the task consisted in going to this zone, doing the yoga pose, and going back to the initial position. The experiment was divided into three blocks, each corresponding to a particular factor, presented in random order. When a given factor was being tested, the two other factors were set at their pre-supposed maximum level (i.e A_f, C_d or P_b). In each block, participants started with the factor tested at a random initial level. A virtual slider, as well as virtual cubes next to the slider corresponding to each level of the factor (see Figure 6.4, center and right), were visible on their left. The order in which the virtual cubes were initially presented was also randomized and the cube corresponding to the random initial level tested was highlighted as being selected. Participants were instructed to proceed as follow. First, perform the task. Second, rate the level by positioning the virtual cube on the slider according to their preference in order to perform the task, ranking it simultaneously by its position relative to the other levels. Third, select another virtual cube with their controller in order to change the level of the factor. They had the possibility to try one level several times when needed to adjust their ratings. When all the cubes were positioned on the slider, the next block could start. The baseline experiment, including the welcoming of participants and consent form signing lasted about thirty minutes.

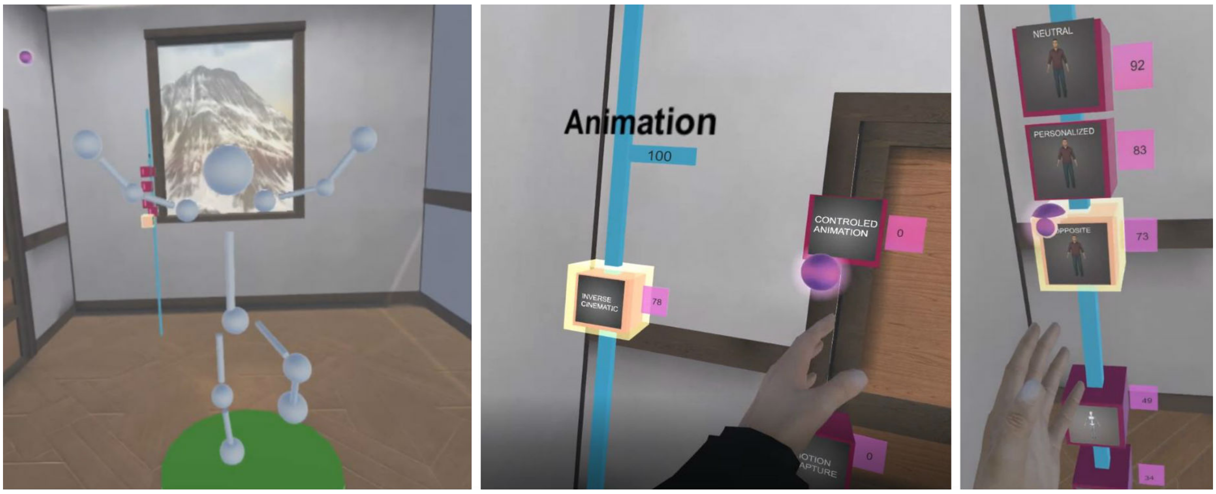


Figure 6.4 – Baseline experiment. Left: user performing the yoga pose with the Stickman appearance. Center and Right: user interacting with the scale to select and rate a given level of Control and appearance factors.

6.3.2 Recorded Data

There were two dependent variables in the baseline experiment for each factor: the score attributed to each level (from 0 to 100) and the ranking of these same levels between each other (from 0 to 5 for *Appearance*, 0 to 3 for *Control* and 0 to 1 for *PoV*).

6.3.3 Results

For the scores analysis, both the normality and homogeneity of variances assumptions were verified for *Appearance* and *Control*, with respectively the Shapiro-Wilk's Normality test ($p = 0.3009$ for *Appearance*, $p = 0.9766$ for *Control*) and Bartlett test ($p = 0.3994$ for *Appearance*, $p = 0.1569$ for *Control*). For *PoV* the homogeneity was verified ($p = 0.1159$) but not the normality. A one-way ANOVA analysis was thus performed for *Appearance* and *Control* and showed significant differences between mean scores of levels ($[F_{1,95}=425.72,\ p < .0001]$ for *Appearance*, $[F_{1,57}=232.57,\ p < .0001]$ for *Control*). Tukey's post-hoc tests ($\alpha = .05$) were conducted to check significance for pairwise comparisons. For *Appearance*, A_a was scored significantly lower than all other levels ($p<.05$). A_b, A_c and A_d were all only significantly lower than A_f ($p<.05$). For *Control*, C_a, C_b and C_c were all significantly lower than C_d ($p<.0001$). Wilcoxon tests were conducted for *PoV* and showed that the P_a was scored significantly lower than P_b ($p<.05$). The mean scores of levels for each factor are represented in Figure 6.5, bottom.

Regarding the ranking analysis, the normality and homogeneity of variances assumptions were not verified leading to an analysis for non parametric data. Wilcoxon tests showed that

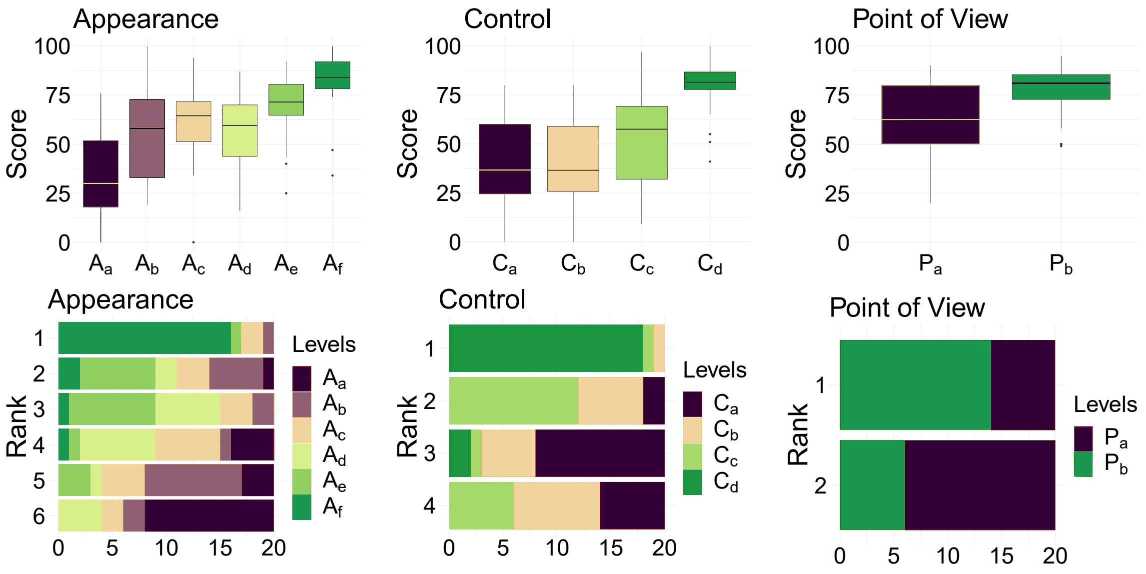


Figure 6.5 – Factors mean scores per levels (top) and rank distribution among participants (bottom).

for *Appearance*, A_a was ranked significantly below all the other levels (p<.05). A_b was ranked significantly below A_e and A_f (p<.05). A_c was ranked significantly below A_f (p<.0001). A_d was ranked significantly below A_e and A_f (p<.05). Finally, A_e was ranked significantly below A_f. Regarding *Control*, C_a was ranked significantly below C_c and C_d (p<.05). C_b was ranked significantly below C_d (p<.0001). C_c was ranked significantly below C_d (p<.0001). Regarding the Point of View, P_a was ranked significantly lower than P_b (p<.05). The distributions of each level per rank for each factor are represented in Figure 6.5, top.

6.3.4 Discussion and Levels Selection

The aim of this experiment was to better understand user preferences and relative ratings of the different levels for each of our factors. Pre-supposed orders had been hypothesized and were partially supported by the results of scores and ranking.

For *Appearance*, the Abstract avatar was highlighted as the lowest level and the Personalized avatar as the highest level among all. The Neutral avatar was ranked significantly lower than the Personalized Avatar and higher than the Stickman and Dummy. However, the scores and ranking between the Opposite and Neutral avatars do not permit to clearly rank one above the others. Another block with close scores and rankings appeared between the Stickman, the Dummy, and the Opposite avatars making it hard to place one above the other. However, among this block, the Stickman was the only one ranked significantly below the Neutral avatar. While those results were mostly expected, it is surprising that the Dummy avatar was rated that close to the non personalized realistic avatars, since it is usually shown that the more realistic the avatar is, the higher the Sense of Ownership towards it is [Argelaguet et al. 2016]. However, this result is in line with Lugrin et al.'s study [2015] showing similar levels of body ownership, as well as enjoyment, towards avatars with different levels of anthropomorphism (e.g. robot and realistic avatars). Moreover, while the higher score given to Personalized avatars compared to Opposite and Neutral ones is in line with Waltemate et al. study [2018], interestingly no significant difference was found in the scores between the Opposite and Neutral avatars. It is nevertheless hard to interpret this result due to the variability of these two levels: participants were choosing themselves these avatars in a global list of 20 avatars per gender. For *Control*, the results only highlighted that Motion Capture was scored and rated higher than all the other levels, placing the Automatic animation, Triggered animation and Inverse Kinematics in the same block. However, among this block, only the Automatic animation was significantly ranked below Inverse Kinematics. While we did not expect such a difference in ratings between the Motion Capture and the Inverse Kinematics, we believe that the fact that the avatar was realistic while testing this factor may have allowed to see more easily potential motion artefacts. For *Point of View*, both scores and ranking results showed a preference for the first-person PoV against the third-person PoV, which is consistent with previous work [Gorisse, Christmann, Amato, et al. 2017].

In addition to gaining insights about user preferences, one of the goals of this baseline experiment was to define an ordered and rated subset of levels for each factor to be used in the subjective matching experiment. This seemed particularly important as the subjective matching experiment presented in the following section required participants to select the next factor to improve in order to increase their SoE, with the goal of matching a previously experienced level of SoE. As introducing levels which were not different enough within a factor might have introduced a bias towards selecting one factor in priority over another, the levels that were not significantly scored or ranked between each other were eliminated from the subset. Therefore, for *Appearance*, the Dummy and the Opposite avatar were removed giving a final ordered and rated subset of: Abstract, Stickman, Neutral and Personalized avatars. Proceeding similarly to the elimination of *Appearance* levels, the Triggered animation was thus removed from the *Control* subset giving the final ordered and rated subset: Automatic animation, Inverse Kinematics, Motion Capture. For the *Point of View*, both levels were thus kept in that order: Third-person PoV, First-person PoV. Table 6.1 summarizes the final levels selected for the subjective matching experiment.

Table 6.1 – Levels selected for the subjective matching experiment

Appearance	Control	Point of View
(A = 0) Abstract avatar	(C = 0) Automatically launched animation	(P = 0) Third Point of View
(A = 1) Stickman	(C = 1) Inverse Kinematics	(P = 1) First Point of View
(A = 2) Neutral realistic	(C = 2) Motion Capture	
(A = 3) Personalized realistic		

6.4 Subjective Matching Experiment

The goal of this experiment was to study the relative contribution of the *Appearance*, *Control* and *Point of View* factors towards the SoE, using the pre-selected levels for each factor obtained from the Baseline experiment. In other words, do users have preferences between those factors when it comes to enhance their SoE towards an avatar?

6.4.1 Tasks

Potential preferences regarding factors influencing the SoE may depend on the task performed in the VE. Indeed, the way users interact with the virtual environment may induce them to look more or less to certain parts of their virtual body, or more generally to pay more or less attention to their virtual body. The presence of collisions between the virtual body and the VE leading to visible feedback of changes in the VE may also influence the perception of the virtual body and thus the SoE. More abstractly, the general context of the interaction, its gamification [Wood et al. 2013; Tuveri et al. 2016] or social aspect [Schuemie et al. 2001] might influence on users' perception towards the overall VE.

For these reasons we hypothesized that the type of action performed by users in the VE would influence the SoE, and therefore designed four different tasks with the goal of covering a wide range of actions that an avatar can do in a VE. First, we designed two tasks involving direct interaction between the virtual body and the VE, one involving the upper-body and one involving the lower-body. Second, we designed a task involving no direct interaction between the virtual body and the VE, but the presence of another virtual character. Finally, we designed a walking task, navigation being a main and one of the most common interaction task in VR. We describe the tasks more in detailed hereafter:

- The *Punching* task consisted in hitting a punching bag, involving the virtual upper-body to be interacting directly with the VE (see Figure 6.1, first).
- The *Soccer* task consisted in kicking a soccer ball, involving the virtual lower-body to be interacting directly with the VE (see Figure 6.1, second).

- The *Fitness* task consisted in following fitness movements instructed by a "fitness teacher" (see Figure 6.1, third).
- The *Walking* task consisted in walking straight while avoiding obstacles on the floor. Low walls constrained the direction of the path to walk on (see Figure 6.1, fourth).

These four tasks were entered in the same general context of a fitness scenario, and participants were immersed in a virtual fitness room in front of a virtual mirror. Participants started on a circular green carpet, and always moved towards another green carpet in front of them to perform the task. The levels of each factor were also the same for the four tasks, with the unique difference that the actual animation of C_0 (Automatically launched animation) was tailored for each task. For the *Punching* task, the automatic animation made the dominant hand punch the punching bag once, while for the *Soccer* task it made the dominant foot kick the ball. For the *Fitness* task the automatic animation displayed the same fitness movements shown by the virtual teacher. Finally, for the *Walking* task the automatic walking solution from FinalIK was applied to animate the feet so that they avoided obstacles when collisions were close, i.e., to step over the obstacles.

A mixed design was chosen for the experiment. Each participant performed randomly only two tasks. This choice was done to reduce experiment duration time and to ensure the engagement of the participants. The design ensured that each task was performed by 10 male and 10 female participants, the order of the tasks was counterbalanced.

6.4.2 Experimental Protocol

Participants started the experiment with a first exposure which had a threefold objective. First, it enabled participants to become familiar with the VE and the tasks to perform. Second, they were instructed to test and become familiar with all the possible levels of each factor. Finally, they then performed the tasks with the best avatar configuration (i.e., with the highest level for each factor: {3,2,1} [1]), and in that case were instructed to focus on their SoE towards the avatar. Considering that the notion of "Sense of Embodiment" was not easy to understand for participants, we detailed the instruction to participants based on the description provided by Kilteni et al. [2012]: "Please be aware of your SoE towards your virtual body while doing the task, considering your SoE as a union of the feeling of ownership you have towards the virtual body, the feeling of control you have over it, and the feeling of being spatially located in this virtual body". After making sure that participants had tested all the improvements they could

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[1] Notation {i,j,k} represents an avatar configuration with levels A_i, C_j, P_k

do towards the virtual avatar, and had memorized their SoE in the best configuration for the tasks, the second part of the subjective matching procedure started. Participants were instructed beforehand that for each task, they would perform several trials in which they would start in a low level configuration of avatar, with the goal of reaching the same SoE they had experienced in the "optimal" configuration. The initial configuration could either be all the factors at level 0 ({0,0,0}) or just one factor at level 1 ({0,0,1}, {0,1,0}, {1,0,0}). Each participant started once with each configuration giving 4 trials per task. In order to minimize ordering effects, the order of the starting configurations for each task was counterbalanced following a Latin square design. Participants then increased a factor by telling the experimenter which factor they wanted to improve. Similarly, they were also instructed to notify the experimenter when their SoE matched the one felt in the "optimal" configuration of avatar. However, participants were asked to keep on making choices to improve the factors until they had reached the final configuration, even if the match happened before reaching the "optimal" configuration.

After completing all the trials for the two tasks, participants completed a post-experiment questionnaire, including the standardized embodiment questionnaire [González-Franco and Peck 2018] , the SUS presence questionnaire [Usoh et al. 2000], as well as a series of questions to rate the factors regarding their preference when improving their avatar. While participants were asked to answer the presence questionnaire and rate the factors focusing on the general experiment (including both tasks), they were instructed to answer the embodiment questionnaire thinking of the avatar in the latest task tested, for which they had matched the high SoE. The whole experiment, including welcoming of participants, reading and signing the consent form, and answering questionnaires lasted around one hour.

6.4.3 Recorded Data

The recorded data includes participants' choices during the experiment as well as the answers to the post-experiment questionnaire. First, there is the "Accepted Configurations", i.e. the configurations at which participants declared to feel an equivalent SoE compared to what they felt in the "optimal configuration". Second, there is the transitions set, meaning the order of improvements made by participants to go from one configuration to another. Finally, there are the answers to the embodiment and presence questionnaire (respectively 7-point and 5-point Likert scale) as well as the ratings made by participants regarding their general preference of factors (7-point Likert scale), all collected from the post-experiment questionnaire.

6.5 Results

In this analysis we made the same assumption than Slater et al. [2010] and Skarbez et al. [2017], namely that the results for each repetition are statistically independent. Since there were performed by the same participant, they are not truly independent, but each trial started with a different initial configuration, forcing participants to reconsider their first choices each time. In this section, we report our analysis according to three measures: the identified Accepted Configurations, the transitions made by participants from the initial configuration to the optimal one, and finally their responses to the post-experiment questionnaire.

6.5.1 Accepted Configurations

To analyse the results concerning the Accepted Configurations, we first computed separately for each task the probability of accepting a configuration (Figure 6.6, left), which corresponds to the number of times participants reported a match of SoE for a given configuration over the total number of accepted configurations (4 trials × 20 participants = 80 accepted configurations in total). If there was no match before the optimal configuration, this configuration was considered as the Accepted Configuration. For example, in the *Punching* task, the configuration {1,2,1} was accepted 9 times, which thus represents 11% of the total accepted configurations. We can observe that configuration {1,2,1} was the most accepted configuration for all tasks except *Punching*, for which the most accepted configurations are spread between configuration {2,2,1} and {3,2,1}.

Second, we computed for each task the conditional probability of participants reporting a match when experiencing a configuration (Figure 6.6, right). For instance, the configuration {1,2,1} in the *Punching* task was attained 35 times, while a match was only reported in 9 trials,

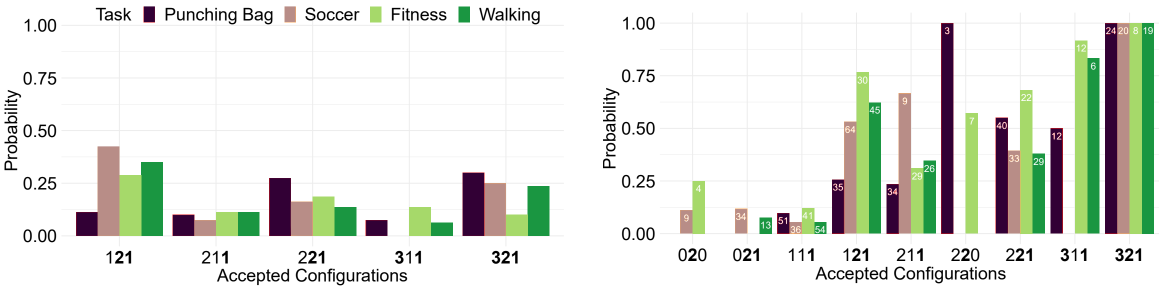

Figure 6.6 – Probability for configurations to be accepted (left) and conditional probability for configurations to be accepted if reached (right). The number written on each bar represents the number of times the configuration was reached. The levels of factors are in bold format when at their maximum. For readability purpose, only configurations with a probability of acceptance higher than 10% are shown.

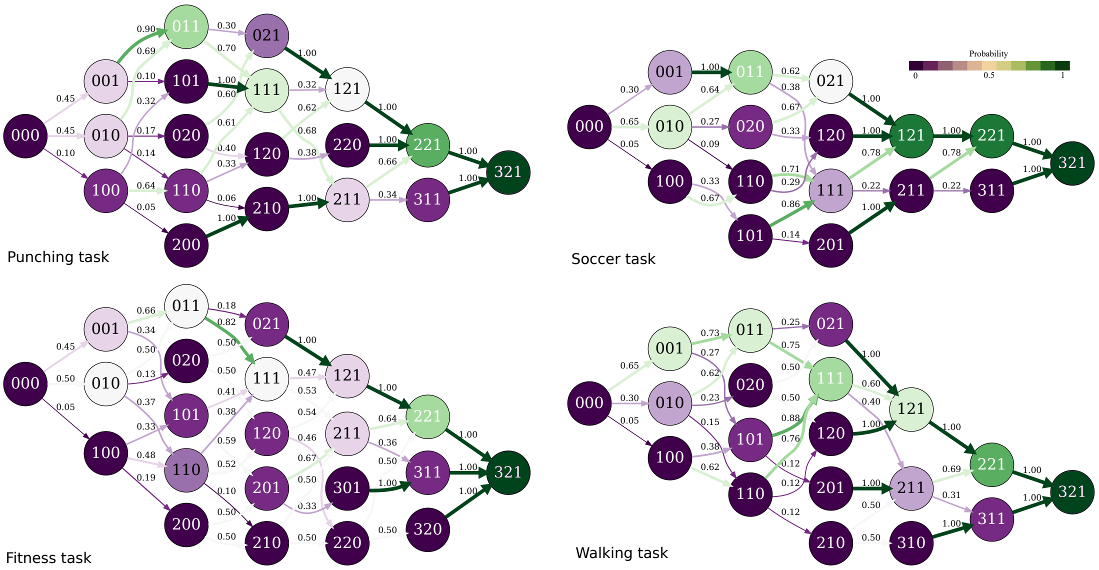

Figure 6.7 – Markov chains representing the transition matrix probability for each task. The color of a node represents the probability that the node is reached. The color and the thickness of the edges represent the transition probability from a given node.

meaning that there is a 26% probability for participants to report a match when attaining this configuration. Results are overall in line with the global probabilities computed, but also give additional information regarding configurations that may not have been often reached, but were mostly accepted when they were. For instance, in *Fitness* and *Walking*, configuration {3,1,1} was only reached 12 and 6 times, but when they were, they had more than 75% chance to be accepted.

Third, we computed for each task the probability of accepting a configuration depending on the participants' gender (see Figure 6.9), since several studies already showed that the perception of the virtual environment [Skarbez et al. 2017] and avatar [Schwind, Knierim, et al. 2017] may vary accordingly. We can observe differences between males and females in *Punching* and *Walking*. In both tasks while males mostly accepted configurations {2,2,1} (44%) and {1,2,1} (45%) respectively in *Punching* and *Walking*, women tended to need higher level of appearance by accepting in majority configuration {3,2,1} (46% in *Punching* and 53% in *Walking*).

6.5.2 Transitions

A transition probability matrix was constructed with the configurations chosen by the participants. Since all participants were asked to improve the configurations until the optimal configuration, there were 6 improvements for each trial starting in configuration {0,0,0} and

5 improvements for the other trials. This makes a total of 21 improvements per participants per task, and a global total for all participants and all tasks of 1680 improvements. This matrix enabled us to compute the probability distribution over the configurations for any given configuration, and the elaboration of a Markov chain for each of the four tasks (Figure 6.7). Each graph represents the probability distribution for each possible transition (configurations most explored are represented in green, while those barely explored are represented in red). The most likely path were also identified for each task and presented in Figure 6.8.

Over all tasks, results show that a clear majority of participants preferred to increase first their level of *Control* or *Point of View* against their *Appearance*. When the first choice was to improve either the *Control* or *Point of View*, the second decision was mostly to improve the other one next, leading to configuration {0,1,1}. At that point, in all tasks except *Soccer* most participants tended to improve their appearance ({1,1,1}), except for the *Soccer* task where the next choice was in majority to increase again the level of *Control* ({0,2,1}). Afterwards, participants mostly attained the same configuration {1,2,1}, by increasing the *Appearance* in *Soccer* or the *Control* in the other tasks. From this configuration, only the *Appearance* could be further increased until the final configuration {3,2,1}.

6.5.3 Post-experiment Questionnaire

From the Presence and Embodiment questionnaires we computed the mean scores for Presence regarding the global experiment (4.70±0.89 (S.D.)) and Embodiment for each task (*Punching*: 5.07±0.69, *Soccer*: 5.23±0.80, *Fitness*: 5.04±0.51 and *Walking*: 5.26±0.75). Kruskal-Wallis tests were performed on embodiment scores showing no significant differences between tasks.

Moreover, mean scores of preference were computed for each factors (see Figure 6.10). Friedman tests showed significant differences between factors for the mean scores of preference attributed to each (p<.001). Wilcoxon tests were thus conducted, showing that *Control* and *Point of View* were both rated on average significantly higher in terms of preference in order to improve the avatar (p<.001).

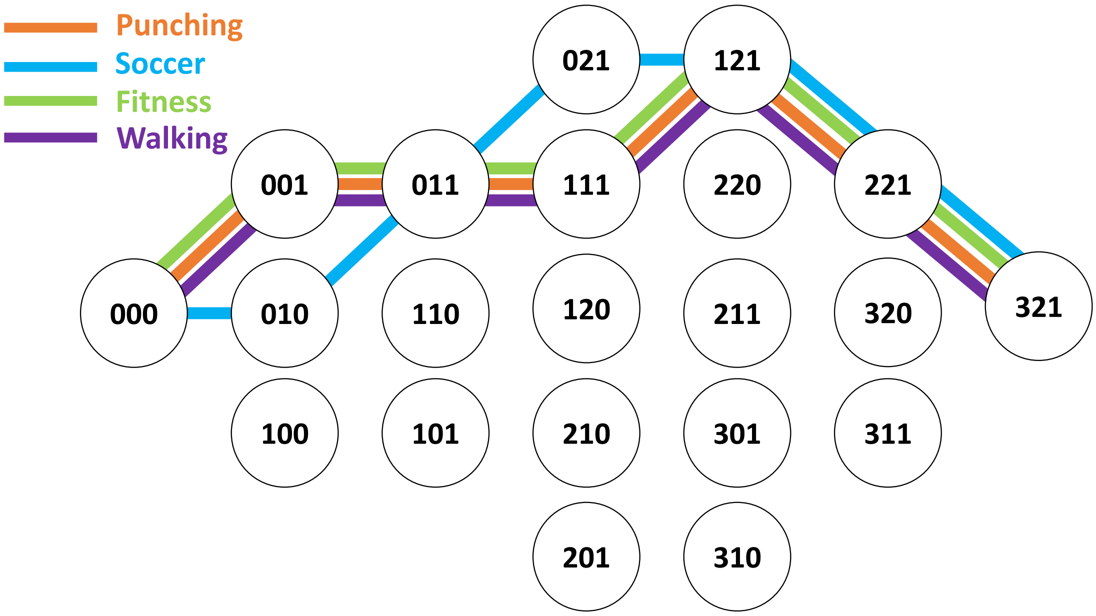

Figure 6.8 – Most likely path for all four tasks.

6.6 Discussion

6.6.1 Importance of Point of View and Control

According to our results, the Point of View and the Control clearly appeared as the preferred factors when improving the configuration of the avatar. This is primarily reflected in the first transition made by most of the participants in all tasks, as they chose to increase first either their level of Control or their Point of View at least 90% of the time whatever the task (90% of the time in *Punching*, and 95% for *Soccer*, *Fitness* and *Walking*). This is also visible in the most likely paths, where increases of the appearance level typically happen late in the paths. The preference regarding control and point of view over appearance is also notable in the most accepted configurations where nevertheless, some differences are to be noted among the tasks. Indeed, the configuration accepted most was {1,2,1} in *Soccer*, *Fitness* and *Walking*, while {2,2,1} and {3,2,1} were the most accepted in *Punching*. It thus seems that for all tasks except *Punching* a low level of appearance (stickman) was enough to match the level of SoE felt in the optimal configuration, while interestingly a higher level of appearance was required in *Punching*. In addition, in the post-experiment questionnaire *Control* and *Point of View* were rated significantly higher than *Appearance* (see Figure 6.10). Overall, these results underline a lower popularity of the appearance factor compared to the control and point of view. It is a rather intriguing result since the appearance of an avatar is a factor widely studied in VR and known to have a strong

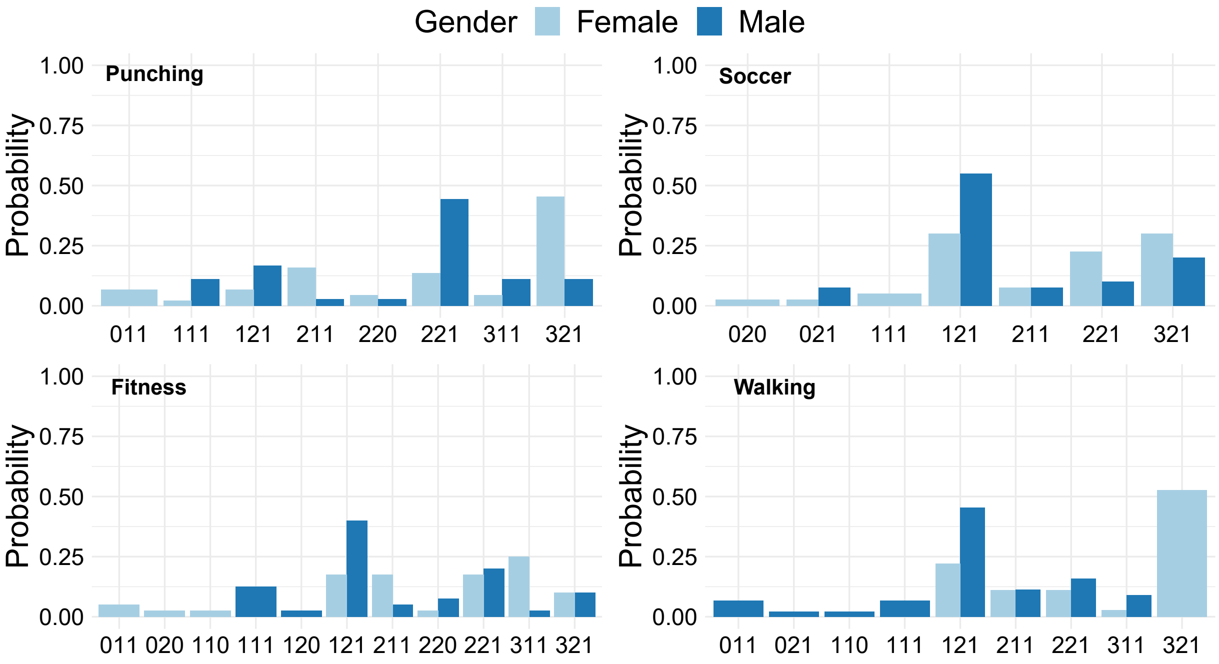

Figure 6.9 – Probability of a configuration to be accepted per task and depending on participants gender.

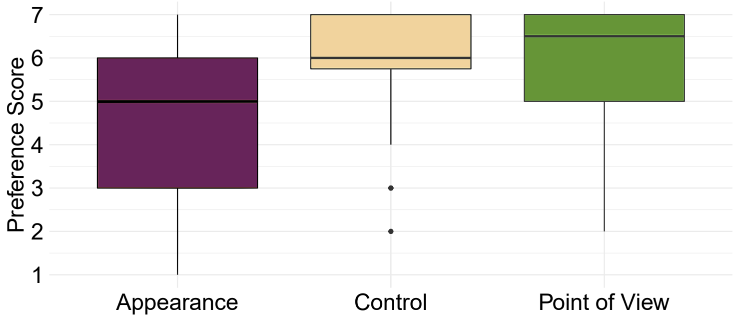

Figure 6.10 – Mean scores from the post-experiment questionnaire according to users' preference of improving the given factor on the avatar.

impact on the sense of body ownership. For instance, Lugrin et al. [2015] and Latoschik et al. [2017] showed that more realistic avatars elicit higher sense of body ownership. Yet, when participants have to choose between the appearance and other factors in order to improve their avatar (with the goal of reaching an equivalent SoE as the one felt in the optimal configuration), they tend to depreciate the importance of the appearance in the improvement process. We may wonder in that case if the control and point of view influence the way the appearance of an avatar is perceived. While potential inter-relations between the control and appearance of an avatar have partially been explored in the context of co-presence [Heidicker et al. 2017], this question remains open when concerning the SoE. In addition, these results also echo the concern raised by Kilteni et al. [2012] regarding the lack of knowledge about the contribution weight on the

SoE of its subcomponents. While this question remains open, we hope our research will serve as a basis for further studies on the subject.

6.6.2 The Control Rush

While the preference attributed to control was reflected in all tasks, an increased interest was especially given to it in the soccer task. This is shown in participants' first choices of improvement: while control and point of view were equally increased first in *Punching* and *Fitness*, control was increased twice more often than point of view in *Soccer*. Furthermore, the most likely paths also highlight the preference of the control at a second stage. While in other tasks the most likely choice was to improve the appearance from configuration {0,1,1} (abstract avatar, IK and first-person PoV), control was mostly chosen instead in *Soccer*. This result is interesting since it shows that in this task, even with very low visual appearance (abstract avatar: only head and extremities represented), the control was increased at its maximum level (from IK to motion capture). This is a rather intriguing result since the major improvement made from IK to motion capture is the gain in precision regarding the position and orientation of middle parts of the body (knees, elbows, etc.), which is not visible with the abstract avatar. We may then wonder why the control was that much improved in that task since the main change between the two levels of control should not have been visible. While our results do not allow to answer this question, it is important to consider the potential influence of the task characteristics. For instance, while participants were precisely instructed that the objective of the task was not to score a goal but only to kick the ball, whether the ball entered or not the goal could still have been interpreted as a success or failure by participants. A possible explanation could therefore be that participants associated the increased level of control with an increased chance of scoring a goal, inciting them to further increase this factor first.

6.6.3 Influence of the task

We describe here other results testifying of the influence of the task performed on user preferences regarding factors influencing the SoE. For instance, we previously presented that the configuration the most accepted was {1,2,1} in *Soccer*, *Fitness* and *Walking*, while {2,2,1} and {3,2,1} were the most accepted in *Punching*. It is interesting that in *Punching*, a task involving an interaction with the upper-body, reaching an equivalent SoE seems to required a higher level of appearance than for other tasks. A main difference between this task and the others is that participants have to look at their virtual body more closely in first-person PoV due to the proximity of the upper limbs with the PoV. While this could partially explain our result, we may also consider that interacting with a punching bag usually requires a consequent strength. It is therefore possible that stickman avatar did not fulfil the visual expectation of a strong body, compared to the realistic avatars, since it does not include any musculature. However, further research would be needed to better understand this result.

Another interesting finding is that in *Walking* the PoV was mostly increased first, rather than the control. Since the navigation task included obstacles on the ground, users were indirectly encouraged to focus on their feet. While it is difficult to say if it is the reason why participants tended to improve their PoV first, it is not the first time that differences in the way users perceived their avatar were highlighted for tasks involving a mirror or locomotion. Moreover, Koilias et al. [2019] showed that the way some factors influence the Sense of Agency varies depending whether the task performed is a self-observation task, an observation-through-mirror task or observation-during-locomotion task. It would therefore be interesting to explore different types of tasks, with or without mirror, and different types of navigation with or without obstacles, to further understand this result.

While it is hard to observe a specific pattern of influence depending of the task, results demonstrate that the preference between factors is not the same in all tasks. This outcome could question whether the results obtained in the baseline experiment were impacted by the specific task chosen. For this reason, it would be very interesting to further investigate whether the task influences the preference of levels of each factor independently, in addition to studying potential preferences in the way levels of different factors are combined together to achieve a satisfying SoE depending of the task.

6.6.4 Limitations and Future Work

The inter-relation between factors influencing the SoE is a complex process. While we tried to address in this study the question of potential user preferences regarding these factors, we believe future research would be valuable to provide more insights on the subject.

In our study, the choice of levels was constrained by the experimental design, where every level of a factor needed to be compatible with every level of all the other factors, as well as by technical limitations. In some cases, we may wonder how the limitations in implementation had an impact on user preferences. For instance, the limitation of our last level of appearance, i.e., the level of personalization of an existing 3D avatar, may explain partially why participants tended to accept configurations with low levels of appearance. Indeed, with such personalized avatars, the avatar body shape rarely matched the users', as well as the exact skin color. However, the current technological advancements are now starting to allow for the production of high-fidelity and highly-realistic avatars, as the ones created using photogrammetry [Waltemate, Gall, et al. 2018] or seeking fidelity of body shape [Pujades et al. 2019]. The addition of such a level of appearance, and more generally the use of a wider range of levels for each factor, would be valuable to more precisely evaluate user preferences and potential accepted configurations. For instance, while we decided in this first study to focus on only two levels of Point of View, inspired by the works of Gorisse et al. [2017] and commonly used in video-games, more levels of Point of View could be considered, including for instance cinematographic aspects.

Furthermore, we may consider the potential influence of having different number of levels for each factor. Indeed, while we believe participants were aware that the same importance was to be given on each choice, their behaviour remains hard to control and we can not fully prevent the case of a user playing “optimally” by upgrading the factor that only takes one improvement. However, we did not observe stronger preferences for the point of view which had the lowest number of levels. We also believe that the choice of adding more levels should be balanced by the fact that having too many levels without significant differences in terms of improvements could also lead to a different bias, hence the reason why a baseline experiment was conducted.

Moreover, while exploring appropriately more levels might still broaden the current findings, we also believe that including other factors in the process would be highly valuable. For instance, the present study only includes feedback about the visual aspect of the avatar. Future work could therefore consider exploring for instance the influence of a multisensory feedback factor, e.g., involving tactile and haptics feedback which are also known to influence the SoE [Kokkinara and Slater 2014; Frohner et al. 2018].

While the subjective matching method used in this study enabled the exploration of factors influencing the SoE without the use of subjective questionnaires or behavioral measurements, we believe it is important to discuss the potential source of unreliability it may contain. First, the subjective matching technique enables the manipulation of a high number of levels and factors in one experiment. However, it also brings the risk of overloading the cognition of participants with all the configurations to remember. We may also consider the difficulty for participants to remember their SoE in the optimal configuration in order to match it from minimal avatar configurations, but also their potential difficulty in understanding the definition of SoE in the first place. Indeed, a description of the SoE to participants with less abstraction would ensure a better uniformity of what this feeling refers to among participants. However, the ratings given to each factor at the end of the experiments by participants, as well as some of their final comments regarding the experiment, testify of a certain guarantee in their choices during the subjective matching experiment: “Appearance is the less important aspect. I preferred the body with spheres or the second avatar”, “The control for me was the most important factor, without control it really felt I was looking like someone else”. Second, another limitation of this method is that when participants accepted lower configurations of avatars, we have no certainty that their SoE was indeed the same as the one felt in the optimal configuration. It would be interesting to assess participants SoE through subjective questionnaires right after participants accepted a lower configuration and after the optimal configuration. However, if this would be done for every trial of an experiment, the additional time added to the whole experiment would have to be addressed as a potential bias source.

6.7 Conclusion

In this chapter, we presented two experiments exploring user preference and perception of three factors commonly found in the literature to influence the Sense of Embodiment in Virtual Reality, namely: the avatar’s visual appearance, the avatar’s control, and the user point of view. Our results first show that appearance of the avatar was given less importance than control or point of view. Second, we found that when it comes to virtual embodiment users do not necessarily need to reach the optimal avatar configuration to feel a fulfilling SoE, suggesting that VE designers may not always need to provide high-end graphics avatars but should provide a high degree of control. Third, we showed that the accepted configurations can vary depending on the task performed, stressing the importance of this aspect for future studies and applications. Taken together, our results provide valuable insights for designers of VR applications involving avatars, showing which factors among the three studied should be prioritized, and paving the way to future studies aiming at better understanding the inter-relations between factors influencing the Sense of Embodiment.

In the next and final part of this thesis, we cover the last layer of the factors representation (see Figure 8.5): factors related to the user. More precisely, in the next chapter, we explore how individual differences in users might influence their perception of the avatar.

PART III

Influence of Users Individual Differences

"Do you know what I do when I feel completely unoriginal? I make a noise, or I do something that no one has ever done before. And then I can feel unique again, even if it's only for a second."

Sam - Garden State

7

Influence of personality traits and body awareness

Abstract:

This chapter reports an exploratory study aiming at identifying internal factors (personality traits and body awareness) that might cause either a resistance or a predisposition to feel a SoE towards a virtual avatar. To this purpose, we present an experiment that we conducted (n=123) in which participants were immersed in a virtual environment and embodied in a gender-matched generic virtual avatar through a head-mounted display. After an exposure phase in which they had to perform a number of visuomotor tasks (during 2 minutes) a virtual character entered the virtual scene and stabbed the participants' virtual hand with a knife.

7.1 Introduction

As shown in Chapter 2, while some studies explored the potential influence of personality traits on the sense of presence in VR, very few works started to explore the link between individual differences and the SoE. In this chapter, we therefore present an exploratory experiment where

Figure 7.1 – From left to right: an example of a trajectory to draw during the experimental task; A view of the scene from behind; Another virtual character stabbing the participants' virtual hand at the end of the experiment to measure their response to the threat on their virtual body.

we investigated the link between "internal" factors (personality traits and body awareness) and the sense of embodiment. One hundred and twenty three participants were embodied in a virtual avatar while taking part in the experiment, which was divided into three phases: adaptation, induction and threat. In the adaptation phase participants were able to freely explore the environment and their avatar, in the induction phase participants had to reproduce a series of visuomotor tasks (see Figure 7.1, left) and in the threat phase, a virtual character appeared in the environment and threatened the avatar's hand with a knife (see Figure 7.1, right). At the end of the experiment, users were asked to fill in an embodiment questionnaire, as well as four additional questionnaires assessing different "internal" dimensions about them: the Big Five Inventory (BFI), the Ten-Item Personality Inventory (TIPI), the Internality, Powerful others and Chance scale (IPC scale) and the Body Awareness Questionnaire (BAQ).

7.2 Experiment

In order to explore the potential influence of personality traits and body awareness on the sense of embodiment, we conducted an experiment in which participants were embodied in a gender-matched avatar. The main experimental task was a visuomotor task involving the upper-body in order to elicit the sense of embodiment over the avatar. After the experiment, participants were asked to fill in subjective questionnaires on embodiment and presence, as well as several personality and body awareness questionnaires.

7.2.1 Participants

One hundred and twenty three participants (age min=18, max=60, avg=30.3±9.0, 58 women and 65 men) took part in our experiment. The majority of them were students and staff from our research center. All participants freely volunteered for the experiment and most of them were curious about virtual reality. They did not receive course credits nor economical compensation. They were all naive to the purpose of the experiment and had normal or correct-to-normal vision. People wearing glasses could keep them if they were not generating any discomfort. All participants gave written and informed consent. The study conformed to the declaration of Helsinki, and was approved by the local ethical committee. Seventy-six participants reported to have no previous experience in VR, twenty-five to have some previous experiences in VR and twenty-two to be experts.

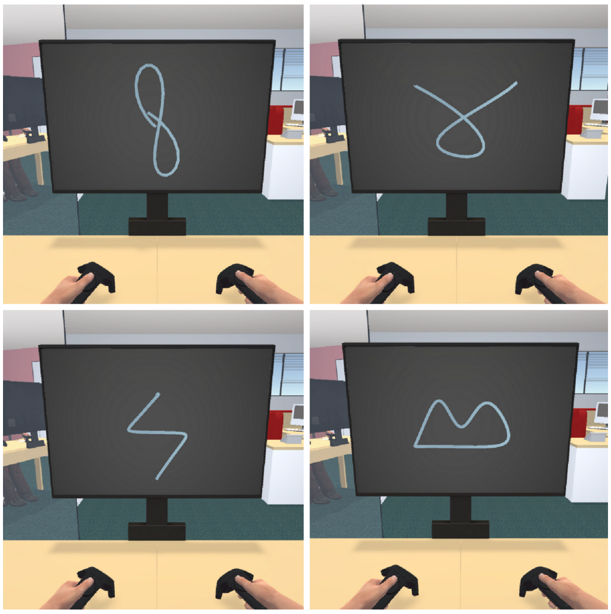

Figure 7.2 – Examples of four trajectories that participants were instructed to perform during the experiment with either their left or their right hand

7.2.2 Experimental Protocol

Before the experiment: Upon their arrival, participants were first briefed about the experiment, read and signed the consent form. They were then equipped with the HMD and the controllers, were asked to sit on a chair in front of the table where the experiment would be conducted, and a calibration phase was performed to adapt the avatar to their dimensions. More precisely, the global scale of the avatar was first adapted to match the height of the participant. Then, participants were asked to take a seated T-pose (reach arms on the side), in order to measure their arm span using both controllers. The distance between the two controllers was therefore used to adjust the avatar's arm length, while the headset position was used to scale the avatar's spine so that the avatar's head position matched the user's one. Participants were then asked to freely discover the environment.We did not impose a fixed time during the acclimation phase. Yet, all participants were encouraged to explore the scene, their avatar, and to look into the mirror. When they were ready, they could start the task.

Experimental task: Participants sat in front of a real table and saw a similar co-located virtual table, while being immersed in the virtual environment from a first-person perspective. They were asked to put their hands on the virtual table (on two white spots) receiving by this occasion passive haptic feedback from the physical table. They hold in their hands the real controllers that were also represented in the virtual world for coherence. A virtual screen was positioned in front of them, on the table, and a virtual mirror was located on their left (Figure 7.1). We chose to use a mirror as it is supposed to induce a greater sense of ownership [González-Franco, Pérez-Marcos, et al. 2010b; Jenkinson and Preston 2015]. Also, we decided to induce the sense of ownership using visuomotor feedback since it has been shown to be stronger than visuotactile synchronisation to induce body ownership [Kokkinara and Slater 2014].

2D trajectories were displayed on the screen (see Figure 7.2), which participants were instructed to reproduce in front of them, using either their right or left hand according to the instruction provided. The trajectories presented were chosen to be relatively simple (number eight, circle, triangle, etc) to avoid a high cognitive load, which could have distracted participants from their avatar and the environment. After each drawing, they had to put back their hands on the white spots on the table. The task lasted two minutes during which participants saw their avatar moving synchronously according to their movements. After the achievement of the task, a virtual character entered the room and stabbed the virtual hand with a knife. We measured the reaction to the threat (hand motion), in order to inspect its potential correlation with the sense of ownership.

After the experiment: Participants were asked to fill in a number of questionnaires. First they filled in a demographic questionnaire, then they answered questions about embodiment, as well as questions about presence. They also filled in several personality questionnaires, and a body awareness questionnaire. Collected data are presented in more detail in Section 7.2.4.

Figure 7.3 – The two avatar models used in our experiments, which were matched to the gender of the participant.

7.2.3 Apparatus

The experiment was developed using Unity 2018.1.6f1. Participants saw the virtual environment through an HTC Vive PRO HMD, while their hand movements were tracked using the Vive controllers. The FinalIK plugin was used to animate the participants' avatar with Inversed Kinematics and to provide visuomotor feedback, based on the participants' head (HMD) and hand (controllers) movements. During the experiment, two avatar models were used to match the participant's gender (see the male and female avatars in Figure 7.3). Despite the relative importance of control over appearance as seen in the previous chapter, appearance is still one of the main contributor to the SoE. Therefore using personalised avatars might lead to high embodiment ratings for most participants [Waltemate, Gall, et al. 2018], which would prevent us from exploring the influence of individual traits on embodiment. We therefore decided to use gender-matched generic avatars to obtain a higher variability in embodiment ratings, i.e., to obtain both low and high embodiment ratings across participants. Also, the animation of the virtual character threatening the participant's hand at the end of the task was recorded using an Xsens motion capture system prior to the experiment, and mapped onto another virtual character (see Figure 7.1, right).

7.2.4 Collected Data

7.2.4.1 Embodiment and Presence Questionnaires

To measure embodiment, participants were asked to fill in the standardised subjective questionnaire proposed by Gonzalez-Franco and Peck [2018]. Participants therefore answered 19 questions on a 7-point Likert scale, from the categories body ownership, agency, location, external appearance and response to external stimuli.

Given the shortness (6 questions) of the Slater-Usoh-Steed (SUS) presence questionnaire [Usoh et al. 2000] typically used in such experiments in the past, we also decided to include this questionnaire. People rated each question on a 7-point Likert scale. Our goal was to confirm previous results linking personality to presence. In particular, assessing how similar our results are to previous work on the relation between personality and presence would also be of value to further validate potential results on the sense of embodiment.

7.2.4.2 Behavioural Response

In addition to the embodiment questionnaire, we recorded participants' hand movements during the threat (character stabbing the participant's virtual hand at the end of the experiment), in order to evaluate how much participants considered the avatar to be their own body. In this situation, typically used in previous studies to provide another measure of the sense of embodiment, participants who feel embodied in their avatar are more likely to remove their hand [Ehrsson, Wiech, et al. 2007], suggesting that they consider the virtual body to be their own.

7.2.4.3 Psychological Variables

As we wished to explore the effect of several aspects of personality and ability on embodiment, we selected a number of questionnaires which participants filled in after the experiment. These questionnaires were chosen to explore aspects we believed could influence embodiment, while ensuring that the duration for answering all these questionnaires was reasonable. Our choice was also based on the few studies conducted on internal factors, using for example body awareness and locus of control as independent variables. Four questionnaires were therefore selected (BFI, TIPI, IPC, BAQ), which are presented below with our corresponding exploratory questions of interest. Research questions were preferred instead of precise hypotheses because of the lack of literature and the wide range of traits evaluated in our experiment. On average, participants took 20 minutes to answer all the questionnaires. As the experiment was conducted on a French campus, we used the French validated translation of these international questionnaires in our experiment. All the Likert scales used are the ones proposed in each validated questionnaire, going from the lower bound (strong disagreement) to the upper bound (strong agreement).

Big Five Personality traits taxonomy is a common way of describing one's personality, even though not the only one that exists. In this model, called the Big Five or OCEAN model [Goldberg 1991], personality is typically described by five dimensions, which are Openness to experience, Conscientiousness, Extraversion, Agreeableness and Neuroticism. While several questionnaires of various complexity exist to assess these personality dimensions (e.g., 240-item NEO PI-R, 44-item BFI) we chose two questionnaires to use in our experiment.

First, we used the 44-item Big Five Inventory (BFI) [John, Donahue, et al. 1991] adapted to French by Plaisant et al. [2010], where each item is rated on a 5-point Likert scale. This is a relatively short questionnaire, compared for example to the 240-item NEO PI-R questionnaire, but still quite complete [John and Srivastava 1999], and used in research [Jacques et al. 2009; Bélisle and Bodur 2010]. It therefore seemed more adapted to an experiment involving several questionnaires. In this regard, a first question of interest was to study whether some personality traits were potentially correlated with the different components of embodiment (Q1).

However, despite the popularity of the BFI questionnaire and its relatively short length (44 items), being able to evaluate quickly how a user's personality traits would affect embodiment prior to a VR experience would be greatly improved if shorter questionnaires could be used. Therefore, we decided to include a second personality questionnaire, namely the Ten Item Personality Inventory (TIPI) [Gosling et al. 2003], and used the French version [Storme et al. 2016], where each item is rated on a 7-point Likert scale. In particular, our goal was to study the extent to which the TIPI questionnaire would enable us to explain embodiment felt in VR compared to the more complete BFI questionnaire (Q2).

Our research questions related to the influence of Big Five personality traits on the sense of embodiment were therefore:

> **Q1: Do some of the users' Big Five traits are correlated with their sense of embodiment in VR?**
>
> **Q2: Do TIPI and BFI questionnaires show similar personality traits correlations with the sense of embodiment in VR?**

Locus of Control (LoC) (i.e., the degree to which people believe that they have control over the outcome of events in their lives as opposed to external forces beyond their control) is another set of personality traits, which was demonstrated to have an influence on the sense of presence [Murray et al. 2007; Wallach et al. 2010] and on the sense of agency [Jeunet et al. 2018]. We therefore included a questionnaire to measure one's LoC, and used the common 24-item IPC scale [Levenson 1981], translated in French by Loas [1994], using a 6-point Likert scale. This questionnaire determines LoC according to three dimensions: Internal, Powerful others and

Chance. These dimensions typically mean that someone with an external LoC will tend to think that everything happens because of fate (chance type of locus) or powerful people (powerful others type of locus), while someone with an internal LoC will tend to think that he can change events with his own will and actions.

As a previous study [Jeunet et al. 2018] showed that an internal LoC is positively correlated with the sense of agency, we expected to find the same results in our study (Q3). Moreover, while this seems in agreement with the fact that the LoC is directly related to the action, there is no information about the possible influence of LoC on the sense of ownership. Therefore, we investigate whether ownership could also be correlated with an internal LoC (Q4), since some studies found that the sense of ownership and the sense of agency are based on similar processes and can strengthen each other [Kalckert and Ehrsson 2012; Dummer et al. 2009].

Our research questions related to the influence of internal and external LoC on the sense of embodiment were therefore:

> **Q3: Is an internal LoC positively correlated with the sense of agency, as previously found [Jeunet et al. 2018]?**
>
> **Q4: Is the sense of ownership also correlated with an internal LoC?**

Body Awareness is a cognitive ability that makes us aware of our body processes. Because it can change the way we perceive our real body, there is a possibility that it could also influence the perception of our virtual body. While body awareness was not found to influence the RHI in the physical world [David, Fiori, et al. 2014], another study did show that the other way, it could be disturbed by the body ownership illusion [Tsakiris, Prabhu, et al. 2006]. Furthermore, to our knowledge, no studies were conducted to investigate its influence on the sense of embodiment in VR. We therefore decided to also include this personal ability in our study, and used the 18-item Body Awareness Questionnaire (BAQ) [Shields et al. 1989], where each item is rated on a 7-point Likert scale, translated in French by Dumont [2013]. This questionnaire is a self-report assessment of the body awareness, estimating the attention and consciousness we have of our body processes, often used in research because of its high reliability and validity compared to other self-report instruments [Mehling et al. 2009].

Our research question related to the influence of body awareness on the sense of embodiment was therefore:

> **Q5: Is body awareness correlated with the sense of embodiment?**

Table 7.1 – Statistical summary of the embodiment questionnaire responses, for each question we report the median and the first and third quartiles. If there was a significant difference between the men and women answers, we report the summary for each group. O: body ownership, A: agency, L: self-location, EA: external appearance, T: threat perception

ID	**Questions**	**Median[Q1,Q3]**	
		Men	Women
O1	I felt as if the virtual body was my body	4 [3,5]	
O2	I felt as if the virtual body I saw was someone else	3 [2,4]	4 [3,5]
O3	It seemed as if I might have more than one body	2 [1,4]	
O4	I felt as if the virtual body I saw when looking in the mirror was my own body	4 [2,5]	
O5	I felt as if the virtual body I saw when looking at myself in the mirror was another person	3 [2,5]	5 [3,6]
A1	It felt like I could control the virtual body as if it was my own body	6 [5,6]	
A2	The movements of the virtual body were caused by my movements	7 [6,7]	
A3	I felt as if the movements of the virtual body were influencing my own movements	2 [1,4]	
A4	I felt as if the virtual body was moving by itself	1 [1,2]	
L1	I felt as if my body was located where I saw the virtual body	6 [4, 6.5]	
L2	I felt out of my body	2 [1,4]	
EA1	It felt as if my (real) body were turning into an “avatar” body	3 [1,5]	
EA2	At some point it felt as if my real body was starting to take on the posture or shape of the virtual body that I saw	2[1,5]	
EA3	At some point it felt that the virtual body resembled my own real body, in terms of shape, skin tone or other visual features	2[1,4]	
EA4	I felt like I was wearing different clothes from when I came to the experience	3[1,5]	
T1	I felt that my own hand could be affected by the knife	2 [1,5]	
T2	I felt fear when I saw the knife	2 [1,5]	
T3	When the knife appeared above my hand, I felt the instinct to remove my hand from the table	1 [1,5]	
T4	I had the feeling that I might be harmed by the knife	2 [1,4]	

7.3 Results

In order to analyse the link between internal factors and the sense of embodiment, Section 7.3.1 first explores the relationship between the embodiment scores (ownership, agency, self-location, external appearance and threat perception) and the Big Five, IPC and body awareness data. The data from the TIPI questionnaire are not discussed as there were no significant results (**Q2** is therefore answered negatively). Then, Section 7.3.2 analyses the behavioural responses and Section 7.3.3 the presence results.

7.3.1 Embodiment

Before conducting the following analyses, we analysed the potential effects of gender and experience in VR on the embodiment questionnaires. Regarding gender, we performed Mann-Whitney tests for each question trying to find significant differences over such potential confounding factors. The analysis only showed two significant differences for body ownership related questions (O2 and O5) between male and female participants, while no significant differences were found for the rest of the questions and factors. A summary of embodiment answers is presented in Table 7.1, separated by men and women answers when relevant. In order to avoid that such differences add noise to the rest of the analysis, the population was split into two groups (men and women) for the body ownership analysis. Regarding experience in VR and video games, we used Pearson correlations to see a potential influence on embodiment. We only found a positive correlation between agency and the experience in video games. For this reason, experience in video games is only reported in the section of Agency.

As we ran the same analysis for each aspect of embodiment, we summarise the procedure here for clarity. More precisely, we ran a separate Polychoric Principal Components Analysis (Polychoric PCA) for each aspect of embodiment on the different questions, as Polychoric PCA takes into account the ordinal nature of Likert scales. This type of PCA has already been used in similar studies [Slater, Navarro, et al. 2018]. As mentioned previously, a separate Polychoric PCA was run on men and women data in the case of ownership. As proposed in the standard questionnaire [González-Franco and Peck 2018], we used the empirical Kaiser criterion to automatically select the number of principal components explaining sufficient amounts of variance, then performed a PCA with this number of components using an oblimin rotation, enabling us to interpret the selected components (see the summary of the obtained components in Figure 7.4, and exact values in Tables 7.5, 7.6, 7.7, 7.8 and 7.9. Pearson correlations were then computed (see summary in Table 7.2) to explore potential links between the different components of embodiment and the internal factors questionnaires results. As we did not find results for the sense of self-location, this part was removed from the analysis.

A multiple linear regression was performed when correlations were found for a given component, as in other cases it would be difficult to find a good model with variables that are not correlated with the studied component. We used a backward stepwise method to select the best predictors, using the Akaike Information Criterion (AIC), i.e. we started with all the variables and progressively removed them so as to minimise the AIC value. We chose the AIC over the adjusted R^2 as it also accounts for the complexity of the model [Faraway 2004]. All the multiple linear regression models computed are summarised in Table 7.3.

7.3.1.1 Body Ownership

As answers to body ownership questions were significantly different for men and women, we did two separate analyses for men and women participants.

Men. Two components were selected ($O_{PC1,M}$ and $O_{PC2,M}$), which explained 65% of the variance. $O_{PC1,M}$ was mainly influenced by the questions O1, O2, O4 and O5, while $O_{PC2,M}$ was mostly influenced by O3.

We only found a positive correlation between $O_{PC1,M}$ and the chance type of LoC (r = 0.248,

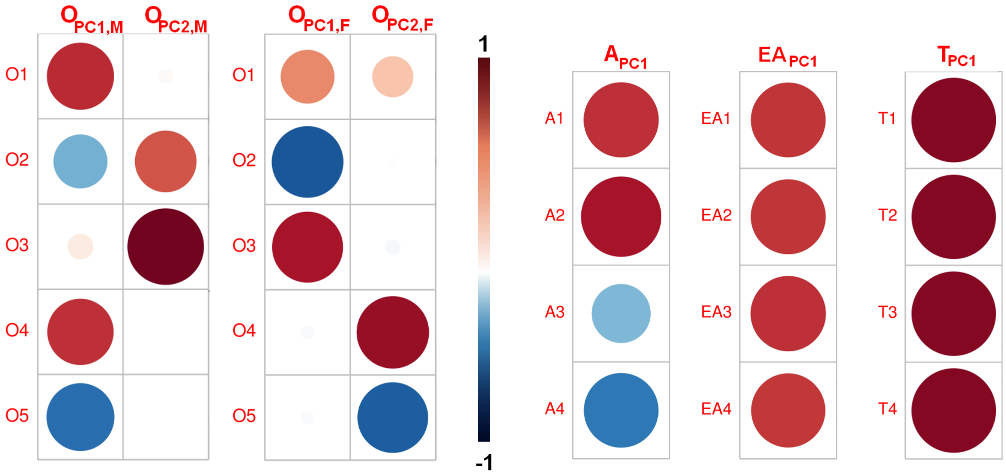

Figure 7.4 – Contributions (i.e. weights) of the embodiment questions to the different components (O$_{PC1,M}$ and O$_{PC2,M}$ (for men), O$_{PC1,F}$ and O$_{PC2,F}$ (for women), A$_{PC1}$, EA$_{PC1}$, T$_{PC1}$)

p = 0.047). As we did not find correlations between O$_{PC2,M}$ and any of the variables, we do not consider it further.

We performed a multiple linear regression for O$_{PC1,M}$ using the different psychological variables. We obtained a model with internal LoC, chance LoC and body awareness (adjusted $R^2 = 0.169, p = 0.003$).

Women. Two components were selected (O$_{PC1,F}$ and O$_{PC2,F}$), which explain 63% of the variance. O$_{PC1,F}$ was mainly influenced by the questions O1, O2 and O3, while O$_{PC2,F}$ was mostly influenced by O4 and 05.

Then, we found a negative correlation between openness and O$_{PC1,F}$ ($r = -0.293$, $p = 0.026$), as well as positive correlations between O$_{PC2,F}$ and both the chance type LoC ($r = 0.366$, $p = 0.005$) and the powerful others LoC ($r = 0.427$, $p < 0.001$).

The linear regression for O$_{PC1,F}$ gave us a model with openness, conscientiousness, internal LoC, powerful LoC, chance LoC and body awareness (adjusted $R^2 = 0.239$, $p = 0.002$).

7.3.1.2 Agency

One component was selected (A$_{PC1}$) which explains 48% of the variance. It was mainly influenced by the questions A1, A2 and A4. We found a positive correlation between A$_{PC1}$ and the internal LoC ($r = 0.248$, $p = 0.006$). The linear model found for A$_{PC1}$ was composed of agreeableness, internal LoC and body awareness ($R^2 = 0.079$, $p = 0.005$). We also found a positive correlation between A_{PC1} and the level of experience in video games ($r = 0.184$, $p = 0.04$).

7.3.1.3 External Appearance

One component was selected (EA_{PC1}), which explains 51% of the variance and was influenced positively by all the questions on appearance (EA1 to EA4). We only found correlations with the internal LoC ($r = 0.195$, $p = 0.031$) and chance LoC ($r = 0.201$, $p = 0.026$).

However, as it seemed surprising that external appearance was simultaneously influenced by opposite (i.e., internal and external) types of LoC, we performed further Pearson correlations separately on the male and female populations, and found that the external appearance was more strongly related to the internal LoC for men ($r = 0.306$, $p = 0.013$) and to the chance LoC ($r = 0.311$, $p = 0.017$) for women.

We performed two multiple linear regressions, by separating male and female populations. For men, the optimised model was composed of neuroticism, internal LoC and chance LoC (adjusted $R^2 = 0.169$, $p = 0.002$). For women, the optimised model was only composed of chance LoC (adjusted $R^2 = 0.081$, $p = 0.017$).

7.3.1.4 Threat Perception

One component was selected (T_{PC1}), which explains 84% of the variance. All the questions about threat perception (T1 to T4) contributed positively to this component. A positive correlation was found with neuroticism ($r = 0.258, p = 0.004$). The linear regression gave us a model with agreeableness and neuroticism (adjusted $R^2 = 0.088$, $p = 0.001$).

7.3.2 Threat Response

In order to evaluate participants' response to the threat in a more objective manner, we also computed their accumulated right hand motion (the stabbed hand) during the threat period to determine whether they reacted or not to this threat. More precisely, we computed the accumulated right hand motion between the moment when the knife was above the hand (approximately 0.5s before the stab) and the moment when the character removed the knife (approximately 1.5s after the stab). Six participants were removed from the analysis because of missing data (controllers positions were not saved), one because he/she removed his/her hand without holding the controller, and one because he/she removed his/her hand before the stab.

Across participants, the average accumulated hand motion was 9.15 ± 19.7 cm (median=1.93cm; min=1.05cm; max=114cm), which was positively correlated with the threat perception score ($r = 0.561, p < 0.001$). In addition, we computed Pearson correlations between the participants' accumulated hand motion and their psychological variables, to determine if their personality traits or abilities would influence the degree to which they reacted to the threat, but we did not find significant correlations.

However, as the threat response can also be considered as a binary variable (whether participants reacted or not), we then performed a further analysis by computing a multiple logistic regression model on whether participants reacted or not. In particular, we considered that participants reacted to the threat if their accumulated hand motion was greater than $5cm$ (threshold experimentally identified from the experimenter's records of whether participants actually reacted). With this criterion, 30 participants were considered to have reacted to the stab out of the 115 participants kept for this analysis. We then used AIC to select the variables to remove from the multiple logistic regression model, and found a model only composed of neuroticism ($\beta = 0.027$, $p = 0.022$) and chance LoC ($\beta = -0.062, p = 0.140$).

7.3.3 Personality Influence on Presence

As previously mentioned, we also asked participants to answer presence questionnaires to assess how similar our results on the relation between personality and presence were from previous work, as well as to strengthen potential results on the sense of embodiment.

While we used Polychoric PCA to analyse the results of embodiment, previous work on presence commonly used a simple mean score over the SUS questions. In order to compare our results to previous work, we therefore followed the same procedure. As for the sense of embodiment, we studied Pearson correlations to identify potential links between presence and personality traits. We found positive correlations with agreeableness ($r = 0.227$, p = 0.012) and with the internal LoC ($r = 0.203$, $p = 0.024$).

We performed a multiple linear regression which gave us a model composed of agreeableness, neuroticism, internal LoC and chance LoC (adjusted $R^2 = 0.134$, $p < 0.001$) (see Table 7.4.

7.3.4 Other Interesting Results

In order to get a clearer understanding of the potential relations between the different aspects of embodiment, we also computed Pearson correlations between all the components that relate to the sense of embodiment. Across men and women participants, we first found a positive

Table 7.2 – Pearson correlations for ownership (men and women), agency, external appearance, response to threat and presence

	$O_{PC1,M}$	$O_{PC1,F}$	$O_{PC2,F}$	A_{PC1}	EA_{PC1}	T_{PC1}	Presence
Openness		-0.293*					
Conscientiousness							
Extraversion							
Agreeableness							0.227*
Neuroticism						0.258**	
Internal				0.248**	0.195*		0.203*
Powerful others			0.427**				
Chance	0.248*		0.366**		0.201*		
Body awareness							

$(* : p < 0.05 \;\; ; \;\; ** : p < 0.01)$

correlation between external appearance (EA_{PC1}) and threat perception (T_{PC1}) ($r = 0.327$, $p < 0.001$), showing that participants tended to be more sensitive to the threat on their avatar when they also rated higher questions on external appearance.

As body ownership analyses were performed separately on men and women, because of significant differences in answering some of the questions, we also looked at correlations separately in this context. First it is interesting to note that we found a positive correlation between external appearance (EA_{PC1}) and all the men and women ownership components ($O_{PC1,M}$: $r = 0.345$, $p = 0.005$; $O_{PC2,M}$: $r = 0.287$, $p = 0.020$; $O_{PC1,F}$: $r = 0.564$, $p < 0.001$; $O_{PC2,F}$: $r = 0.593$, $p < 0.001$). For both men and women, we also found a correlation between the threat perception (T_{PC1}) and their first ownership component ($O_{PC1,M}$: $r = 0.355$, $p = 0.004$; $r = 0.289$, $p = 0.028$).

7.4 Discussion

This experiment on the sense of embodiment, in which 123 participants took part, is to our knowledge the first VR experiment measuring embodiment as well as several personality traits and body awareness. Our aim was to explore how internal factors (individual differences) could modulate virtual embodiment experiences. In this section, we discuss the obtained results for each aspect of embodiment, as well as future work.

Table 7.3 – Multiple linear regression models for embodiment
($* : p < 0.05$; $** : p < 0.01$; $*** : p < 0.001$)

$\mathbf{O}_{PC1,M}$

Variables	β	$Pr(> \lvert t \rvert)$
Internal	0.059	0.003 **
Chance	0.054	0.004 **
Body Awareness	-0.013	0.038 *

$\mathbf{O}_{PC1,F}$

Variables	β	$Pr(> \lvert t \rvert)$
Openness	-0.010	0.021 *
Conscientiousness	-0.008	0.068
Internal	0.038	0.006 **
Powerful	-0.026	0.055
Chance	0.038	0.010 **
Body Awareness	-0.010	0.044 *

$\mathbf{O}_{PC2,F}$

Variables	β	$Pr(> \lvert t \rvert)$
Extraversion	0.006	0.112
Powerful	0.036	0.024 *
Chance	0.027	0.099
Body Awareness	-0.008	0.174

$\mathbf{A}_{PC1}$

Variables	β	$Pr(> \lvert t \rvert)$
Agreeableness	0.005	0.122
Internal	0.026	0.003 **
Body Awareness	-0.006	0.077

$\mathbf{EA}_{PC1}$ **for men**

Variables	β	$Pr(> \lvert t \rvert)$
Neuroticism	0.285	0.036 *
Internal	1.865	0.001 ***
Chance	0.843	0.102

$\mathbf{EA}_{PC1}$ **for women**

Variables	β	$Pr(> \lvert t \rvert)$
Chance	1.230	0.017 *

$\mathbf{EA}_{PC1}$ **for women**

Variables	β	$Pr(> \lvert t \rvert)$
Chance	1.230	0.017 *

Table 7.4 – Multiple linear regression models for presence

Presence		
Variables	β	$Pr(>\lvert t\rvert)$
Agreeableness	0.018	0.008 **
Neuroticism	0.008	0.095
Internal	0.061	0.001 **
Chance	0.046	0.010 *

Table 7.5 – Contributions (i.e. weights) of the different questions to the men ownership components

	$\mathrm{O}_{PC1,M}$	$\mathrm{O}_{PC2,M}$
O1	0.740	
O2	-0.475	0.623
O3	0.102	0.966
O4	0.722	
O5	-0.756	

Table 7.6 – Contributions of the different questions to the women ownership components

	$\mathrm{O}_{PC1,F}$	$\mathrm{O}_{PC2,F}$
O1	0.471	0.272
O2	-0.846	
O3	0.829	
O4		0.864
O5		-0.822

Table 7.7 – Contributions of the different questions to the agency component

	A_{PC1}
A1	0.722
A2	0.827
A3	-0.443
A4	-0.713

Table 7.8 – Contributions of the different questions to the external appearance component

	EA_{PC1}
EA1	0.716
EA2	0.719
EA3	0.727
EA4	0.705

Table 7.9 – Contributions of the different questions to the threat perception component

	T_{PC1}
T1	0.919
T2	0.913
T3	0.915
T4	0.917

7.4.1 Sense of Embodiment

For each aspect, we first discuss the global obtained scores. While we used PCA for the analysis, here we mention scores for the different aspects using summation equations provided by [González-Franco and Peck 2018] in order to provide a simpler interpretation for discussion. Then we discuss the results concerning the Big Five traits and the locus of control, and finally potential other noticeable results like differences between men and women or interesting correlations with other variables.

7.4.1.1 Body Ownership

Overall, body ownership scores were in the average ($M = 4.3; SD = 1.1$), with a high variability, i.e. people presenting either low or high levels of body ownership. This could be explained either by the individual differences of participants and/or the use of a generic avatar. Our results also show that the question related to the co-located virtual body (O1) was rated higher than the question related to the avatar visible in the mirror (O4), which seems to suggest that the use of a mirror could be detrimental in some cases, as it might emphasise the appearance differences.

Regarding the influence of personality traits, our results first demonstrated that *body ownership is to some extent correlated with external dimensions of the locus of control*, both for male and female participants. This result answers Q4, but not as expected. Since the sense of ownership and agency usually strengthen each other, we expected ownership to be correlated with an internal locus of control, as is the case for agency. However, our results suggest that body ownership is actually more influenced by external dimensions of the locus of control. Typically, people with an external locus of control tend to think that things happening to them depend mostly on the influence of other people or chance. Therefore, our results suggest that people with an external locus of control might feel embodied in a virtual representation more easily than people with an internal locus of control.

In conducting this study, we expected some of the Big Five personality traits to influence ownership (Q3). However, our results did not show any evidence of such an influence. Similarly, we also measured body awareness, i.e., the cognitive ability of being aware of body processes, which we supposed could also influence embodiment in general (Q5). Even though body ownership scores tended to be low for people with high body awareness, the results were not significant. Similarly, experience in VR and video games, which could have influenced body ownership, did not show any influence, suggesting that experience in virtual-type applications does not influence how one's accept a virtual body as its own.

Finally, we also noticed that women gave higher scores to the question O5, which means that they had a higher feeling that the avatar in the mirror was someone else. It is difficult to assess what might explain this result, but a possible assumption would be the fact that the avatars were not personalised. More precisely, it is possible that the male avatar had more average physical characteristics regarding the population of the experiment than the female avatar (brown hair and average build for male avatar compared to blond hair and skinny body for female avatar). While this result shows that differences can appear between different user groups as it was previously found in other studies [Schwind, Knierim, et al. 2017], and that the visual resemblance of the avatar might also influence these results, further studies would be necessary to better understand these influences.

7.4.1.2 Agency

On average, agency scores were high ($M = 5.1; SD = 0.7$), showing that participants felt in control of the avatar's movements. First, we found that the sense of agency is correlated with the internal dimension of the locus of control, which positively answers our question Q3 and is in line with previous findings [Jeunet et al. 2018]. Therefore, it seems that *people who feel a higher control on happening events tend to also experience a higher control of their virtual body*, and might therefore feel more responsible of the avatar's movements. However, we did not find correlations with the other personality traits from the Big Five. Interestingly, we also found a positive correlation with the level of experience in video games, showing that *the more people have experience in video games, the more they feel they have control over their avatar*. This result is also supported by participants (with high gaming experience) feedback, who reported that they felt in control both because the avatar was moving well according to their movements and because they felt that there was no latency in the displayed movements.

7.4.1.3 External Appearance

External appearance scores were overall below average ($M = 3.0$; $SD = 1.3$), meaning that participants did not really have the feeling that the avatar looked like them. Our results showed that the acceptance of the avatar's external appearance was positively correlated with the internal and the chance dimensions of the locus of control. This result is particularly surprising as it shows that external appearance is simultaneously influenced by opposite (internal and external) types of locus of control. However, further exploration showed that these effects were due to external appearance being more correlated with an internal locus of control for men, but with a chance locus for women. However, these results cannot be interpreted in terms of differences between men and women's personality traits and can only be interpreted separately. Women with a chance locus of control tend to have higher external appearance scores, i.e., they tend to think that the self-avatar is a look-alike avatar. This result is similar to the one obtained for ownership, which was also correlated for women with an external locus of control and could be explained for the same reasons evoked previously. In contrary, men with an internal locus of control tended to have higher external appearance score. This means that men thinking that they can control their own life tend to more believe their avatar is similar to them. Although those interesting results also highlight differences between groups of population, deeper studies would be required to clarify these effects.

7.4.1.4 Threat Perception

Threat perception scores were particularly low ($M = 2.9$; $SD = 2.0$), which is in accordance with the number of people who actually reacted to the stab (30 out of 115 whose reactions to the threat were recorded). This is supported by the feedback from several participants who did not react to the threat and reported that they felt that the virtual environment seemed "safe", and therefore did not feel threatened. Moreover, we found that threat perception was correlated with neuroticism. Since people with a high degree of neuroticism tend to be anxious, it is understandable that these same people were more impacted by the introduction of the threat. The fear of a threat is also commonly considered as an expression of the sense of ownership in studies exploring the sense of embodiment. If we observed in our results that the threat perception was also correlated with one component of ownership for both men and women, it is however not enough to make a link between neuroticism and the sense of ownership.

In addition to assessing threat through questionnaires, we also measured the right hand motion in reaction to the stab. The model which better explained the differences between people who reacted from those who did not react was also influenced by neuroticism, which confirms the influence of neuroticism on the response to threat.

7.4.2 Presence

Our goal in investigating whether we found similar effects of personality traits on presence than previous studies was to validate that our experimental setup provided a similar basis than previous studies, which would therefore simultaneously strengthen the value of any results found for the influence of personality traits on the sense of embodiment. As expected, we found similar correlations than in previous studies, namely a correlation between presence and agreeableness [Sacau et al. 2005], as well as between presence and an internal locus of control [Wallach et al. 2010].

7.4.3 Future Work

The different aspects of embodiment are very complex processes, and our results confirm the fact that more studies are required to further our understanding of these processes. In particular, while we expected personality traits or cognitive abilities to enable us to explain why some people easily believe in the illusion of being embodied in a virtual body, and why others are in the contrary totally refractory, we found that mostly the locus of control personality trait was able to explain some of these differences. Therefore, we are still far from uncovering all the mechanisms involved in eliciting high senses of embodiment in every user, which would also require further inter-disciplinary collaborations. For example, cognitive models trying to explain the sense of ownership is still an on-going topic of research evolving regularly [Braun, Debener, et al. 2018] and involving different theories.

In this experiment, we decided to investigate individual factors in relation to the sense of embodiment, which had not been deeply explored yet in virtual reality. For the first study on this topic, we therefore chose a number of questionnaires to explore the potential influence of personality traits. Given the amount of personality and cognitive models and questionnaires in the literature, it was therefore not possible to be exhaustive, and we decided to focus on some of the most common models (i.e., Big Five, Locus of Control, Body Awareness). Further studies exploring the influence of other traits and inter-personal aspects could also be interesting to improve our understanding, e.g., absorption, empathy, cultural differences, racial information.

In this study, we also chose to focus on a standard visuomotor task, as it was previously shown to be stronger than visuotactile synchronisation to induce body ownership. Conducting similar experiments with more complex tasks would therefore also be of interest, e.g., to evaluate the influence of the cognitive load or of the type of stimulation. For instance, people reported that they tended to forget the avatar while doing the task, therefore exploring tasks involving more the actual user's virtual representation would also be interesting.

Finally, one interest of our experiment was to explore whether our results could suggest the use of a novel pre-experiment questionnaire to assess/predict the degree to which users would feel embodied in their avatar. For this reason, we included both a longer and a shorter version of the Big Five personality questionnaires (i.e., BFI and TIPI), in order to evaluate if a shorter questionnaire could lead to similar results in assessing the sense of embodiment from personality traits. While our current results were not conclusive in this regard (Q1, Q2), to be able to create such a questionnaire could prove a valuable tool in the future to adapt the virtual experience to the user in order to maximise his/her sense of embodiment. This would however also require additional knowledge about which adaptations are more fitted for some categories of users than others.

7.5 Conclusion

In this chapter, we presented a first experiment exploring the influence of several personality traits and body awareness on the sense of embodiment. Overall, our main results suggest that the locus of control is correlated with some of its components: an internal locus of control is correlated with agency, while an external locus of control seems to be linked to body ownership. While the locus of control provides some information about the sense of embodiment, our results suggest that Big Five personality traits and body awareness are not the main influencing factors. We only found a positive correlation between neuroticism and the reaction to threat (both in embodiment questionnaires and in actual behavioural responses). This study is therefore another step towards a better understanding of the sense of embodiment. In particular, we would like in the future to be able to exploit the user's profile to offer him a customised experience, such as adding cues enhancing body ownership in cases when the user is considered to be unresponsive to body ownership. Another possibility could also involve increasing other aspects, such as presence or enjoyment, for people who are refractory to some aspects of the embodiment, instead of desperately attempting to elicit this illusion.

"One is always a long way from solving a problem until one actually has the answer."

Stephen W. Hawking

8

Conclusion

The global objective of this work was to improve avatars in VR by enhancing the understanding of how users perceive their avatars and which factors influence their SoE towards them. In particular, we aimed at enriching current knowledge regarding factors related to avatar characteristics but we also had the objective to widen the range of potential factors of influence, by exploring the impact of VE and users' characteristics on the SoE. Pursuing this goal, we therefore identified three objectives of research:

- Exploring the impact of VEs characteristics on the SoE.
- Investigating avatar related factors of the SoE with an innovative approach.
- Probing the potential impact of users' individual differences on the SoE.

In order to meet these objectives, we presented in **Part I** three studies exploring the impact of VE characteristics on the SoE. In Chapter 3, we first studied the influence of VR shared environments on the SoE, showing that the presence of another user in the VE does not impact the SoE. We have also found that sharing the VE with another user significantly increases user engagement in the VE. Taken together, these findings lead the way for VR-application designers to identify the important features to consider in order to develop multi-user VEs.

Secondly in Chapter 4, we further investigated the influence of shared VEs on the SoE in the context of a new concept that we introduced: virtual co-embodiment. We showed that while sharing the control of the same avatar, participants were good at estimating their level of control towards the avatar, and that they even tended to overestimate their feeling of control in certain conditions. We also highlighted that a personality trait of participants (Locus of Control) was negatively correlated with the participants' perceived feeling of control, which partially motivated the study conducted in Chapter 7 exploring the impact of individual differences on the SoE. Overall, these findings not only corroborate and extend previous studies, but they also pave the way for further applications in the field of VR-based training and collaborative tele-operation applications in which users would be able to share their virtual body.

In Chapter 5, we expanded our investigation of VE-related factors, by exploring the impact of another widely exploited characteristic of VEs: their capacity of providing users strong emotions. More precisely, we were interested in the introduction of threats in VR, which is common in VR applications, especially in the context of embodiment studies, and we explored its impact of the SoE. Taken together, our results suggest that embodiment studies should expect potential changes in participants behaviour while doing a task after a threat was introduced, but that threat introduction and repetition do not seem to impact users SoE towards their avatar.

In **Part II**, we tackled another objective of this thesis: exploring interrelations within avatar-related factors. To do so, we used for the first time in virtual embodiment studies the method of subjective matching, in a experiment that we described in Chapter 6. The subjective matching method enabled us to highlight that the appearance factor was given less importance than the control and point of view factors. In addition, we also showed that when it comes to virtual embodiment, users do not necessarily need to reach the optimal avatar configuration to feel a fulfilling SoE, suggesting that VE designers may not always need to provide high-end graphics avatars but should provide a high degree of control. Finally, we discovered that the type of task performed in the VE has an impact on user's factor preferences. Taken together, our results provide valuable insights for designers of VR applications involving avatars, showing which factors among the three studied should be prioritized, and paving the way to future studies aiming at better understanding the inter-relations between factors influencing the Sense of Embodiment.

In **Part III**, we finally addressed our last objective: exploring the impact of the user (individual differences, personality traits, etc.) on the SoE. To that aim, we presented in Chapter 7 a study exploring the impact of user personality traits and body awareness on the SoE. We showed that the Locus of Control of participants was highly correlated to their SoE, which corroborated previous studies. However, Big Five personality traits as well as body awareness were not found to be of strong influence on the SoE. This study is therefore another step towards a better understanding of the SoE, and paves the way for further works investigating how other individual differences may influence users' SoE towards their avatar.

8.1 Short Term Perspectives

The research conducted during this thesis has highlighted several limitations of avatars in VR, on both technical and perceptive aspects, leaving room for open questions and future perspectives. In this section, we therefore suggest several directions of improvements for all the contributions made in this thesis.

8.1.1 Evalutating Users Experience of Avatars

In this manuscript, several user studies were conducted in order to assess the impact of distinct factors on the SoE among the three following layers: the User, the Avatar and the VE. In these studies, the SoE was assessed using the current methods at the time of the respective experiments: subjective questionnaires inspired from Botvinick and Cohen [1998] or Gonzales-Franco and Peck [2018], and objective measures with threat introduction. However, in spite of the several attempts to obtain a standardized embodiment questionnaire in the latest research [González-Franco and Peck 2018; Roth and Latoschik 2019], there exists no such validated questionnaire to this day. The use of subjective questionnaires in wider contexts is furthermore being more challenged for that it depends on users' own understanding of questionnaires, which may be impacted by many internal differences between users [Jahedi and Méndez 2014; Slater 2004]. In addition, another concern in regards to subjective questionnaires was raised by Insko [2003] about the study of presence in VR, stressing out that because they are post-immersion, they do not measure potential impact of time on the subjective presence nor the potential influence of events during the experiment. Such constraints stimulated our will to investigate the SoE with other means, as it was done in Chapter 6 with the subjective matching technique. However, it was the first time such method was applied to the study of the SoE. For this reason, we believe more research using this method would be valuable in order to highlight additional tracks of improvement. A possible approach for instance would be to combine the subjective matching method with other measures: subjective questionnaires or response to threat. Furthermore, there has been some effort in exploring the potential of physiological and behavioral measures of the SoE [Banakou, Groten, et al. 2013; Meehan et al. 2002]. However, while these measures are interesting for being objective and continuous, they tend to lack of accuracy and are difficult to generalize [O'Donnell and Eggemeier 1986; Luong et al. 2020].

Overall, we believe that further research should be undertaken in order to achieve more efficient ways to evaluate users' SoE towards their avatar.

8.1.2 Implications of the Task towards the SoE

The research presented in this manuscript also thrown up many questions in need of further investigation regarding the impact of the task in user studies involving avatars. The first studies exploring the SoE in VR did not involve a specific task: the participant was rather static, or performed very basic movements with the limbs [Yuan and Steed 2010]. With the increase and diversification of possible applications of avatars in VR, many studies tended to study the SoE towards avatars in more specific context. For instance, in the study of Galvan Debarba et al. [2017], several stages of action were designed such as reaching targets appearing around the participant or walking from one position to another. In addition, in the study of Latoschik et al. [2017], the effect of avatar realism on the SoE is assessed in a context of social interactions. In Chapter 3, while exploring the impact of users sharing the same VE on their SoE, it can be noted that a strong choice of design was made regarding the task they were performing: a gamified task involving competitiveness. This task enabled us to highlight several levels of engagement depending on users sharing or not the VE, which is interesting to know when developping VR applications involving several users. However, the increase in users' engagement may have reduced the awareness of participants about their virtual body, which is detrimental for the context of embodiment studies, where it is important that participants pay attention to their virtual body. In addition, the interaction capabilities of the task were strongly constrained for that participants remained seated and could not therefore experience a full body control over the avatar. In Chapter 6, we observed that when participants were asked to improve their avatar in order to reach a speficic SoE previously experienced, their choices tended to vary between the four tasks proposed. This raises the following question: What is the best avatar configuration to a given task? While tasks can be extremely variable, we believe it would be interesting to further explore how the type of task may impact users SoE towards their avatar. Yet, another question seems important to highlight at this point: In applications involving avatars, what does matter the most - that users feel perfectly embodied in their avatar or their performance while doing a task through the avatar? While the fact that both are directly linked may seem to have been taken for granted, we believe it would be relevant to make more distinction between both aspects of the user experience. Indeed, we hope that in the future, such distinction and tasks exploration will help to better understand which type of avatars should be designed for which specific applications, in order to provide users with the best experience possible, fulfilling the application objectives in terms of user embodiment and performance.

8.1.3 Exploring Further the Role of Mirrors in Embodiment Studies

When designing embodiment experiments, another characteristic of the study must be defined in addition to the choice of task performed by users: the presence or not of a virtual mirror in the VE that would allow users to see their avatar reflection. The studies of the two Chapters (3 and 6) raised questions regarding the use of mirror in embodiment studies. Indeed, the use of a mirror is commonly used in order to enhance the sense of ownership [González-Franco, Pérez-Marcos, et al. 2010b; Spanlang, Normand, Borland, et al. 2014], yet in Chapter 3 we interestingly did not found a significant increase in ownership in the mirror condition. A possible explaination could be that in the mirror participants would see more easily animation artefacts of their avatar due to limits of the used avatar animation methods. In addition, while the potential impact on the SoE of morphology differences between the avatar and the user's body were not explored in this study, we may wonder if seeing the avatar's reflection in a mirror would reinforce the perception of this difference and by extent possibly influence users' SoE. Further research would be necessary to investigate this question. In Chapter 6, we also argued that the presence of a mirror had possibly interfered in the impact of the task on the results. Indeed, while the navigation task in the referred study included obstacles on the ground, users were indirectly encouraged to focus on their feet and were therefore potentially less inclined to look at their mirror reflection. To this day, we believe some questions remain open: To induce a strong SoE towards an avatar, is it better that participants look at their virtual body directly or through a mirror? Looking directly at one's own avatar is constrained by the field of view of the HMD, although the current development of such medium seems to go towards HMDs with wider fields of view. Overall, while several works started to tackle the role of the mirror observation in the perceived SoE [Koilias et al. 2019], we believe that more research into the exploration of methods ensuring awareness of the virtual body in the context of different type of tasks would be very valuable.

8.1.4 Effect of Co-localization on the Sense of Embodiment in shared Virtual Reality Environments

A common perspective was highlighted from both our studies involving shared VEs (Chapter 3 and 4): exploring the effect of co-localization on the SoE in shared VEs. Indeed, both studies were conducted with pair of participants sharing both the same virtual and physical space and they were sitting next to each other. This implied that users eventually saw each other physically and could potentially talk and hear each other directly, which could have introduced additional implications in terms of social interactions. In a study of Podkosova et al. [2018] it was shown that users behave differently in shared VEs depending of if they were co-localized or not. More precisely, differences in participants locomotor trajectories were observed while they had to avoid colliding with each other. For this reason, we believe it would be interesting to pursue these works by exploring how co-localization impacts users' SoE.

8.1.5 Deepen the Research about the Influence of Users Individual Differences on the Sense of Embodiment

In Chapter 4, we had started to explore the relation between the user individual differences and the SoE by investigating the link between the sense of agency and the Locus of Control. This exploration was followed in more depth in Chapter 7, where more personality traits were explored as well as body awareness regarding their potential influence on the SoE. However, due to the amount of personality traits, cognitive models and questionnaires in the literature, the study was limited in the exploration of individual differences impact. In future work, it would therefore be interesting to further explore the influence of other traits and inter-personal aspects to improve our understanding, e.g., absorption, empathy, cultural differences, user morphology. Furthermore, while this has never been in the focus of any of our studies, we observed several times that results were differents depending on participants' gender (in Chapters 6 and 7). While some studies already started to explore gender bias in virtual embodiement studies [Lopez, Yang, et al. 2019], we believe it would be interesting to further assess the relation between gender and the SoE.

8.1.6 Exploring the link between the Sense of Embodiment and Haptic feedback

Overall, tactile and haptic feedback more generally, have not been highly exploited within the frame of this thesis. In all the studies conducted, participants had controllers in their hand, through which we eventually provided vibrations as tactile feedback for various kinds of interaction. Yet, on several occurrences questions were highlighted regarding the link between haptic feedback and the SoE. The study conducted in Chapter 5 raised questions regarding the impact of mismatch between tactile feedback and virtual threat on the SoE. Indeed, in our study, the threat was associated with a tactile feedback, but no noticeptive feedback, which somehow is not "coherent". The notion of coherence in virtual environments has been shown to be of great importance to have participants react realistically to the virtual environment [Slater 2009]. However, while tactile feedback is often modulated by its synchronicity in embodiment studies, to our knowledge the impact of coherence mismatch between of the tactile feedback and the seen stimuli in the VE on the SoE remains unexplored and would therefore be interesting to investigate. Moreover, while we explored in Chapter 6 the relative preference of three important factors: the appearance, the control and the point of view, we believe it would be really interesting to replicate this study involving haptic feedback as an additional factor, declined with different levels (e.g. realistic vs non realistic haptic feedback).

8.2 Long Term Perspectives

Up to this day, we are very far from avatars as imagined in James Cameron's movie. Despite the impressive advancements brought by research on exploring better ways to create avatars and understand how users perceive them, some idealistic specificities of avatars are still out of reach. For instance, in James Cameron's movie, the main character, who lost the ability of using his legs, is able to control a full-body avatar without making any body movements, by the "mysterious" technology of the booth he lays in (see Figure 8.1, left).

Figure 8.1 – Left: picture of the movie Avatar from James Cameron. Right: face animation technology used in Avatar movie.

In the last years, many research works explored the potential of brain-computer interfaces, recently defined as "any artificial system that transforms brain activity into input of a computer process" [Si-Mohammed et al. 2019], as a way to interact with the VE [Lotte et al. 2012]. Less explored nonetheless, is the potential of such technology to control avatars in virtual reality. If seminal works explored the faisabily of such system [Longo, Castillo, et al. 2014], the current state of knowledge regarding brain-computer interfaces does not allow such control as in James Cameron's movie. A long-term perspective in regards to avatars enhancement could therefore be the further investigation of brain-computer-interface-based control of avatars in virtual reality.

Another major point that keeps us away from James Cameron's avatars is the capacity to animate the face of avatars according to actors' face expressions and mirror their emotions. The technology used to animate the blue creatures from the movie according to users' expressions is also used to animate the face of agents and virtual characters in various digital contents. However, such system is hardly compatible with the wearing of an HMD. Recent research developed an "Embodied Realistic Avatar System" that involves body motion and face animation [Aseeri et al. 2020]. Yet, in this proposed solution, the participant from which an avatar is animated according to body and face movements is not immersed in VR, it is the other user who is wearing an HMD that can therefore appreciate the high quality avatar animated in real time. Recently, several works started to explore how to get around the issue of wearing an HMD to asses users' face expressions, notably by exploring diverse solutions to transcript users' expression through the avatar [Olszewski et al. 2016]. However, these solutions do not provide yet efficient and robust live face animation of avatars, which we believe, would be a valuable path of exploration for the achievement of high quality avatars.

Finally, in spite of the consequent progress on providing users with multi-sensory feedback from their interaction though the avatar, notably with haptic vests or gloves, or auditory feedback, we still fail at giving to users the integrality of the sensations they should feel through their avatars. In a long term perspective, Avatars should therefore be able so provide users with all the sensations they experience through their physical body in real time and coherence with their interactions in the VE. In the meantime, I hope the work conducted in this thesis will contribute as a little step towards movie-like avatars and will encourage further research to investigate the possible avatars of tomorrow, and explore how users will perceive them through the study of the sense of embodiment.

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Résumé long en Français de la Thèse

Contribution à l'Étude des Facteurs Influençant le Sentiment d'Incarnation Envers un Avatar en Réalité Virtuelle

Cette thèse, intitulée **“Contribution à l’Étude des Facteurs Influençant le Sentiment d’Incarnation Envers un Avatar en Réalité Virtuelle”**, présente des travaux de recherche qui visent à améliorer l’expérience d’être incarné dans un avatar en réalité virtuelle, en comprenant mieux comment les utilisateurs perçoivent leur avatar à travers leur sentiment d’incarnation.

La plupart du temps, les gens ont une image très différente des avatars : “ma photo de profil sur facebook”, “mon personnage quand je joue aux jeux vidéos”, ou même le film technologiquement révolutionnaire de James Cameron [1]. Dans l’ensemble, si un avatar semble toujours très lié au “soi”, il peut correspondre à des choses très différentes selon le contexte, c’est pourquoi il est important de définir le cadre de référence dans lequel nous considérons les avatars : dans cette thèse, nous nous intéressons aux avatars dans le contexte de la Réalité Virtuelle (RV).

Parler de RV déclenche aussi souvent des réactions intéressantes, car l’association des deux mots "virtuelle" et "réalité" tend à intriguer les gens. Pourtant, s’ils peuvent d’abord apparaître ensemble comme un oxymore, leurs définitions ne sont pas incompatibles. Combinés ensemble, les deux mots renvoient à un concept distinct dont la définition reste sous l’influence de sa nouveauté : en évolution. Dans ce manuscrit, nous nous référons à la définition suivante d’Arnaldi et al. [2003].

Réalité Virtuelle

> “La réalité virtuelle est un domaine technique et scientifique qui utilise l’informatique et les interfaces comportementales afin de simuler le comportement d’entités 3D dans un monde virtuel qui interagissent en temps réel entre elles et avec l’utilisateur en immersion pseudo-naturelle par des canaux sensori-moteurs.” [Arnaldi et al. 2003]

Depuis les premières années de la RV, des recherches ont été menées pour créer un contenu virtuel dans lequel les utilisateurs peuvent faire l’expérience d’un monde simulé et virtuel comme s’il était réel. Afin de fournir une telle illusion, divers stimuli visuels, auditifs ou haptiques sont fournis par la simulation en réponse aux actions des utilisateurs [Sherman and Craig 2003]. La congruence entre tous ces stimuli et les actions des utilisateurs, également appelée “contingences sensorimotrices”, caractérise fortement l’immersion vécue en RV. Cela se traduit par exemple par le changement de l’affichage visuel en fonction des mouvements de tête de l’utilisateur [Slater 2009]. En outre, le niveau d’immersion des utilisateurs dépend

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[1] Cameron, James, et al. *Avatar*. 20th Century Fox, 2010.

également des systèmes d'affichage visuel utilisés pour fournir la simulation, tels que les systèmes basés projection (par exemple, les CAVEs (pour "Cave Automatic Virtual Environment") et les visiocasques (voir Figure 8.2). Au cours des dernières années, les visiocasques grand public sont devenus de plus en plus disponibles, ce qui a conduit à une large diffusion des applications de RV développées pour ces équipements, dans lesquelles les utilisateurs peuvent être immergés avec une occultation visuelle totale du monde physique. Cette particularité des visiocasques de cacher totalement le monde physique pose les bases de cette thèse : lorsque les utilisateurs portent un visiocasque, ils ne peuvent plus voir leur corps physique.

Figure 8.2 – Exemples des deux principaux systèmes d'affichage visuel pour expérimenter la RV. A gauche : Un utilisateur immergé dans le cave Immersia à Rennes, France. A droite : Un homme utilise un visiocasque et des joysticks dans les bureaux de MCR à Lille, France. Philippe Huguen / AFP - Getty Images file

Dans le monde physique, notre corps est un point de référence naturel qui nous permet de nous situer spatialement dans le milieu environnant. Pourtant, lorsque nous sommes immergés en RV avec un visiocasque, nous perdons les informations visuelles de notre corps physique dans le processus. Alors que le sens de l'auto-mouvement et de la position du corps, également connu sous le nom de proprioception, nous donne des indices concernant la position des différentes parties du corps [Tuthill and Azim 2018], l'exécution d'interactions précises qui impliquent le corps reste difficile sans retour visuel. Cela a pris d'autant plus d'importance avec l'objectif de la RV de fournir des interactions réalistes et efficaces avec les Environnement Virtuels (EVs). C'est pourquoi les questions liées à la représentation des utilisateurs dans l'EV sont devenues de plus en plus importantes ces dernières années. La représentation d'un utilisateur dans l'EV est communément appelée "avatar".

Les Avatars en Réalité Virtuelle

Bien que le terme “avatar” soit également défini de nombreuses façons, nous nous référons à la définition générale donnée par Sherman et Craig [2003] :

Avatar

> “Un objet virtuel utilisé pour représenter un participant ou un objet physique dans un monde virtuel ; la représentation (généralement visuelle) peut prendre n’importe quelle forme.” [Sherman and Craig 2003]

Cette définition est particulièrement intéressante car elle combine deux points importants : premièrement, un avatar représente toujours une entité physique, soit une personne (le plus souvent), soit un objet. Par conséquent, un personnage virtuel contrôlé par une intelligence artificielle ne peut être référé à un avatar dans le cadre de cette définition. Deuxièmement, si les recherches récentes ont conduit à la création d’avatars anthropomorphiques de grande qualité, il est important de garder à l’esprit qu’un avatar peut avoir n’importe quel type de représentation, de très abstraite (e.g., représentation géométrique de certaines parties du corps) à très réaliste (e.g., corps entier représenté avec des détails anthropomorphiques) (voir Figure 8.3). Dans le cadre de cette thèse, nous nous concentrons sur les avatars dans le contexte de la réalité virtuelle immersive utilisant des systèmes basés sur les visiocasques. Dans une telle configuration, les utilisateurs peuvent incarner pleinement leur avatar, le contrôler par leurs propres mouvements et peuvent potentiellement le percevoir comme s’il s’agissait de leur propre corps. Le processus d’incarnation dans un avatar peut être représenté par une boucle de perception-action (voir Figure 8.4). Les utilisateurs incarnent un avatar virtuel à travers lequel ils interagissent avec l’EV et son contenu (e.g. les objets virtuels, les autres utilisateurs, etc.). Ils reçoivent un retour d’information multisensoriel de ces interactions qui contribue à leur expérience d’être incarnés dans l’avatar.

La conception d’avatars doit s’adapter à un certain nombre de contraintes techniques et algorithmiques. Par exemple, donner aux avatars un aspect réaliste nécessite une reconstruction exigeante du modèle 3D, et donner aux utilisateurs la possibilité de contrôler leur avatar de manière fluide avec leurs propres mouvements nécessite des capacités de capture de mouvement de haut niveau. De plus, un développement algorithmique complexe est nécessaire pour fournir aux utilisateurs des contingences sensorimotrices en fonction de leur interaction avec l’EV par le biais de leur avatar. L’obtention d’un avatar pleinement fonctionnel est donc un défi en

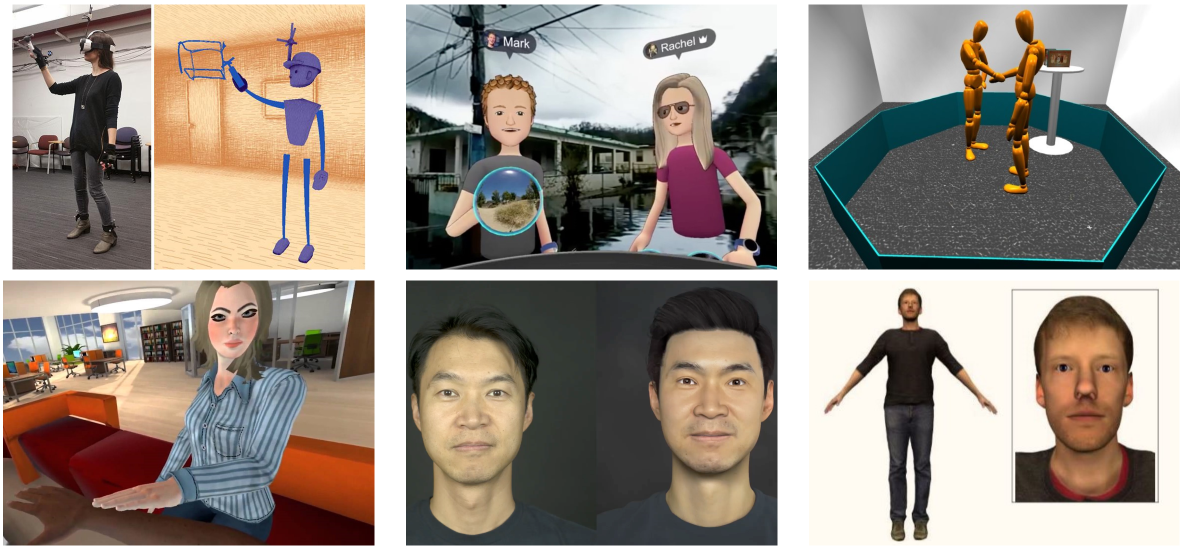

Figure 8.3 – Exemples de différentes représentations d'avatars. En haut, à gauche : Un avatar cartoonisé dans le système de réalité virtuelle Holojam de Ken Perlin. Photographie de Sebastian Herscher ; dessin d'Holojam par David Lobser. En haut, au centre : Un avatar cartoonisé de Zuckerberg, avec la responsable de la réalité virtuelle sociale de Facebook, Rachel Franklin. Photographie par Facebook. En haut, à droite : Avatar mannequin de Roth et al. [2016]. En bas, à gauche : Avatar réaliste du projet beingavatar. En bas, au centre : Le co-fondateur d'ObEN, Adam Zheng, et son avatar photoréaliste. En bas, à droite : Avatar scanné du corps entier et visage provenant de l'étude de Latoschik et al.[2017].

raison des limitations techniques, mais aussi parce qu'il est difficile de comprendre les processus sous-jacents à la perception des avatars. En effet, pour que les utilisateurs puissent interagir de manière réaliste avec l'EV par le biais de leur avatar, il est nécessaire qu'ils “ne fassent qu'un” avec lui, et qu'ils sentent qu'ils possèdent et peuvent contrôler ce corps virtuel. Cette expérience du corps virtuel est communément caractérisée par le Sentiment d'Incarnation (SI) [Kilteni, Groten, et al. 2012] et est largement étudiée afin d'évaluer comment les utilisateurs perçoivent leur avatar et dans quelle mesure ils acceptent ou rejettent ce corps virtuel.

Ces dernières années, de nombreuses études ont tenté de mieux caractériser et étudier le SI en RV afin de mieux évaluer la façon dont les utilisateurs perçoivent leur avatar virtuel. En 2012, Kilteni et al. [2012] ont introduit une décomposition du SI qui a été utilisée pour étudier le SI dans un corps de recherche important. Selon eux, le SI renvoie au sentiment d'être à l'intérieur, de contrôler et de posséder un corps virtuel, et peut donc être décomposé en trois sous-composantes respectives et distinctes : le sentiment de localisation de soi, le sentiment d'agentivité et le sentiment de possession. Cette décomposition a depuis été largement utilisée pour mieux comprendre comment les utilisateurs perçoivent leur avatar. Néanmoins, l'étude du SI est difficile en raison de la difficulté de mesurer un sentiment subjectif. En effet, le SI

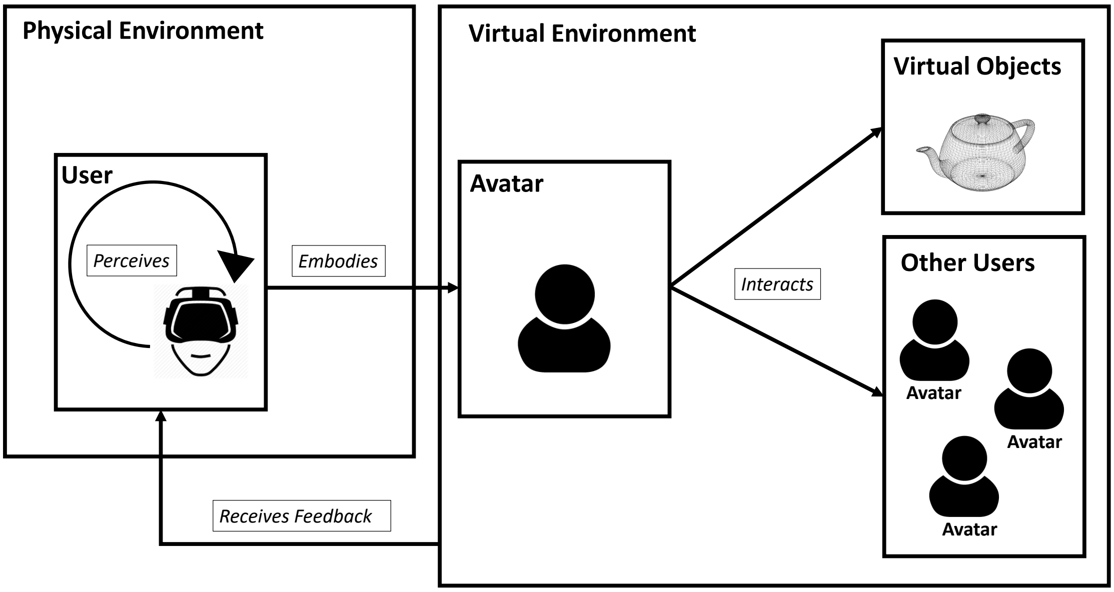

Figure 8.4 – Boucle de perception-action impliquant des avatars. Les utilisateurs du monde physique incarnent un avatar virtuel qui les représente dans l'EV. Par l'intermédiaire de cet avatar, ils interagissent avec l'EV (soit avec des objets virtuels, soit avec d'autres utilisateurs également représentés par des avatars). De cette interaction, ils reçoivent un retour d'information qu'ils perçoivent et qui contribue à la construction de leur expérience cognitive et subjective.

est un *quale* (c'est-à-dire une qualité ou une propriété telle qu'elle est perçue ou vécue par une personne), ce qui le rend difficile à évaluer. Pour cette raison, il a été nécessaire d'explorer les possibilités existantes pour mesurer et évaluer le SI dans le cadre d'études utilisateurs. Différentes méthodologies ont donc été explorées afin de mesurer cette expérience subjective. Parmi ces méthodes, les questionnaires subjectifs [González-Franco and Peck 2018] ont trouvé un usage répandu dans les études d'incarnation, mais d'autres études ont également eu tendance à intégrer des mesures objectives telles que des mesures comportementales (e.g., des changements d'attitude implicites [Banakou, Groten, et al. 2013]) et physiologiques (e.g., la fréquence cardiaque [Meehan et al. 2002]).

Ces recherches ont fourni des informations précieuses pour la conception des avatars en RV en vue d'offrir aux utilisateurs la possibilité d'atteindre un SI élevé. En outre, les études sur le SI ont révélé de nombreuses possibilités nouvelles pour explorer la relation entre le corps et l'esprit [Kilteni, Groten, et al. 2012; Hoyet et al. 2016]. Les avatars en RV permettent des expériences originales car ils peuvent être modifiés et contrôlés de nombreuses manières. Par exemple, il est possible d'être incarné dans un avatar de sexe différent [Peck et al. 2018] ou avec des changements morphologiques tels qu'une main à six doigts [Hoyet et al. 2016]. Ces expériences ont permis de mieux comprendre la perception de notre propre corps et ont montré la plasticité du cerveau dans le cas d'illusions corporelles altérées. D'autre part, ces recherches ont également permis de mieux comprendre comment les utilisateurs perçoivent leur représentation virtuelle en RV et s'ils sont prêts à accepter un corps virtuel qui diffère du leur en termes d'aspect visuel et de schémas de contrôle. En particulier, les applications en psychologie et en sciences cognitives ont bénéficié de ces découvertes au cours des dernières années, en utilisant par exemple l'incarnation d'avatars comme outil pour les thérapies des troubles alimentaires en incarnant des patients dans des corps virtuels de sujets sains [Serino et al. 2019], ou pour sensibiliser les auteurs de violences domestiques en changeant leur perspective envers la victime par l'incarnation d'avatars [Seinfeld et al. 2018]. Les applications des avatars sont désormais largement répandues dans un très large éventail de domaines tels que la formation, l'éducation, le divertissement (e.g., le cinéma immersif), la télémédecine, etc.

Facteurs Influençant le Sentiment d'Incarnation

Dans l'ensemble, les études antérieures sur le SI ont permis de mieux comprendre comment concevoir des avatars plus efficaces en termes d'incarnation. Différents “facteurs d'influence” sont ressortis de ces recherches, principalement en ce qui concerne les choix de conception des avatars ainsi que leurs caractéristiques techniques. Par exemple, il a été démontré que l'apparence de l'avatar est un facteur d'influence essentiel pour susciter le sentiment de possession [Argelaguet et al. 2016; Lin and Jörg 2016], tandis que le contrôle d'un avatar semble avoir un impact majeur sur le sentiment d'agentivité de l'utilisateur [Caspar et al. 2015]. Enfin, le point de vue envers son avatar peut avoir un impact sur l'endroit où l'on se perçoit et modifie ainsi le sentiment de localisation de soi [Gorisse, Christmann, Amato, et al. 2017]. Ces études ont en commun de se concentrer sur des facteurs qui sont centrés sur l'avatar : elles examinent surtout ce qui pourrait avoir un impact sur la perception d'un avatar à travers ses caractéristiques.

Dans cette thèse, nous suggérons une catégorisation des facteurs influençant le SI qui implique plus que l'avatar lui-même. En effet, comme le montre la figure 8.4, un avatar fait partie d'une boucle qui implique plusieurs éléments supplémentaires : l'utilisateur et l'EV impliquant potentiellement d'autres utilisateurs. Bien qu'elles fassent partie intégrante de l'expérience de l'avatar, les caractéristiques liées à l'utilisateur (traits de personnalité, sexe, etc.) et à l'environnement virtuel (interactivité, capacité multi-utilisateurs, etc.) ont rarement été prises en compte dans les études sur le SI. Nous proposons donc une représentation en plusieurs couches, où chaque couche représente un groupe de facteurs potentiels influençant le SI (voir Figure 8.5). Les facteurs appartenant à la couche Avatar et EV peuvent être caractérisés comme des facteurs “externes”, tandis que les facteurs liés à l’utilisateur peuvent être caractérisés comme des facteurs “internes”. Dans ce manuscrit, nous utilisons également cette représentation pour structurer les recherches qui ont été menées dans le cadre de cette thèse.

Champ d’Application et Axes de Recherche

En dépit des idées notables issues des études discutées précédemment, des zones d’ombre subsistent dans notre compréhension de la façon dont les utilisateurs perçoivent leur avatar en RV. Cela limite à son tour notre capacité à améliorer ces avatars afin de renforcer la qualité des expériences utilisateur. En particulier, notre proposition de représentation des facteurs influençant le SI nous a permis d’identifier plusieurs brèches dans l’image d’ensemble, dont nous avons extrait trois axes de recherche principaux, correspondant aux trois couches de notre représentation des facteurs. Nous avons ensuite mis en évidence différentes questions de recherche que nous avons structurées sur ces couches :

— **Environnement virtuel -** L’environnement virtuel dans lequel les utilisateurs sont immergés peut-il avoir un impact sur le SI des utilisateurs envers leur avatar ? Et plus précisément, la présence d’autres utilisateurs dans l’environnement virtuel influence-t-elle le SI de l’utilisateur envers son avatar ?

— **Avatar -** Y a-t-il une contribution dominante entre les facteurs d’influence liés à l’avatar envers le SI ? Certains de ces facteurs devraient-ils être privilégiés dans la création d’avatars ?

— **Utilisateur -** Pourquoi certaines personnes s’incarnent-elles facilement dans leur avatar, alors que d’autres sont plus réticentes à l’expérience ? Les différences individuelles au sein des utilisateurs ou les traits de personnalité influencent-ils la façon dont l’avatar sera perçu ?

Ces axes de recherche sont détaillés dans les sous-sections suivantes, en commençant par la couche externe de notre représentation : l’environnement virtuel.

Influence de l’Environnement Virtuel (Facteurs Externes)

Les EVs peuvent être caractérisés par une multitude de facettes, telles que leur style de rendu ou leur réalisme, leur degré d’interactivité et la quantité de retours sensoriels qu’ils

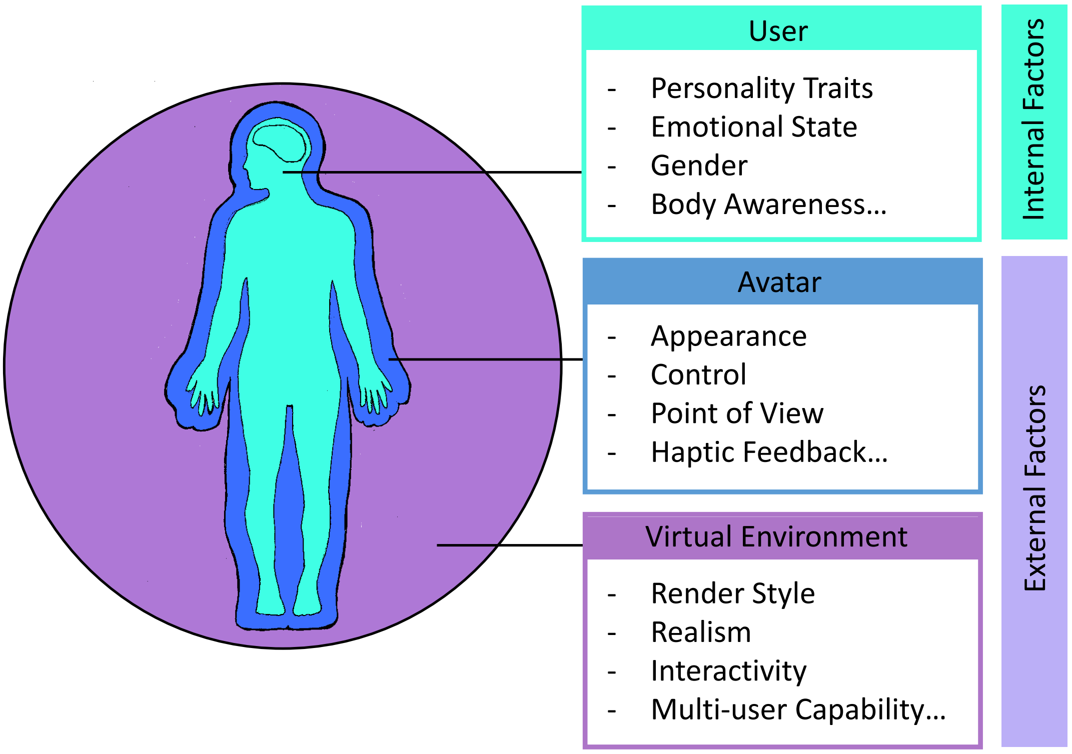

Figure 8.5 – Suggestion de représentation des facteurs influençant le SI : chaque couche représente un groupe de facteurs : l'utilisateur, l'avatar et l'environnement virtuel.

fournissent. Les caractéristiques des EV sont connues pour influencer les expériences de RV des utilisateurs et, plus précisément, pour influencer le sentiment de présence des utilisateurs, un autre *quale* qui fait référence au “sentiment d'être dans le monde virtuel” [Schuemie et al. 2001]. Cependant, l'impact des caractéristiques de l'environnement virtuel sur le SI reste rarement étudié. En particulier, nous avons identifié deux aspects de l'EV susceptibles d'influencer le SI : la dimension sociale de l'EV (c'est-à-dire la présence d'autres utilisateurs partageant le même EV) et l'introduction de menaces envers l'avatar dans l'EV.

Environnements virtuels partagés

De plus en plus d'expériences de RV partagées de haute qualité sont maintenant proposées par les développeurs de RV. Ces configurations permettent à plusieurs utilisateurs d'être immergés dans le même environnement virtuel sans nécessairement être physiquement co-localisés. Ils ont également la possibilité d'interagir simultanément les uns avec les autres et avec l'EV. Ces progrès ont revigoré les intérêts de la recherche dans les EV partagés, e.g., [Brown et al. 2017;

Kuszter et al. 2014; Sharma and Chen 2014]. Afin d'évaluer l'effet de ces EV partagés sur l'expérience des utilisateurs, le sentiment de présence a fait l'objet d'une étude approfondie. Il a été démontré que le fait de voir d'autres utilisateurs dans l'environnement virtuel pouvait être considéré comme une preuve de sa propre existence dans l'environnement virtuel et pouvait accroître le sentiment de présence. Cependant, alors que le sentiment de présence a été étudié dans les EV partagés, les études du SI semblent se concentrer uniquement sur les expériences à utilisateur unique. Il n'est donc pas encore très bien connu comment le partage d'expériences virtuelles avec un autre utilisateur incarné dans un avatar peut influencer son propre SI. Nous avons par conséquent décidé d'explorer cette question dans la thèse.

À cette fin, nous présentons une étude explorant l'influence des environnements virtuels partagés sur le SI des utilisateurs dans le **Chapitre 3**. Nous présentons plus précisément une expérience dans laquelle deux participants partagent le même environnement virtuel et effectuent ensemble une tâche impliquant différents degrés de compétitivité, et nous explorons les effets sur le SI des utilisateurs vers l'avatar et l'engagement dans la tâche virtuelle. Dans le **Chapitre 4**, nous explorons le contexte de l'environnement virtuel partagé un peu plus loin en étudiant l'influence du partage d'un avatar virtuel avec un autre utilisateur. Plus précisément, nous nous sommes intéressés au partage du contrôle de l'avatar, et à la manière dont le poids de contrôle partagé (qui était modulé) influencerait le sentiment d'agentivité et les actions motrices des utilisateurs. Ce travail a été réalisé en collaboration avec Nami Ogawa, une doctorante invitée de l'Université de Tokyo. Nous avons toutes les deux contribué à part égale dans cette étude de recherche.

Menaces dans les EVs

Une autre caractéristique des EVs largement exploitée est leur capacité à transmettre aux utilisateurs un large éventail d'émotions. Pour cette raison, la RV est devenue particulièrement attrayante pour différents domaines de recherche où il est crucial que l'environnement virtuel réussisse à induire des réactions émotionnelles. Cela implique des recherches explorant les réactions émotionnelles des utilisateurs en RV [Diemer et al. 2015] ainsi que des travaux étudiant l'utilisation des menaces virtuelles dans la thérapie d'exposition basée RV pour traiter les phobies [Wald 2004; Tardif et al. 2019]. Un autre domaine de recherche qui nous intéresse plus spécifiquement dans cette thèse, est l'étude de l'incarnation d'avatars virtuels, où l'introduction d'une menace est fréquemment utilisée pour évaluer le SI des utilisateurs envers leur avatar. Plus précisément, plusieurs études ont montré avec succès que le SI était corrélé à la réaction à une menace virtuelle envers le corps virtuel [Yuan and Steed 2010], validant l'hypothèse selon laquelle si les utilisateurs sont bien incarnés dans l'avatar virtuel, ils réagiront physiquement à une menace virtuelle envers leur corps virtuel. Néanmoins, si l'introduction d'une menace virtuelle dans les études d'incarnation virtuelle est largement utilisée, aucune recherche n'a spécifiquement évalué l'impact de la menace virtuelle sur le SI. En d'autres termes, le SI est-il modulé par l'occurrence d'une menace ?

Dans le **Chapitre 5**, nous présentons donc une étude qui explore l'impact potentiel de l'introduction d'une menace sur le SI et ne considérons donc pas l'introduction d'une menace uniquement comme une mesure, mais comme un facteur susceptible d'affecter le SI. Ce chapitre explore également les impacts peu connus des répétitions de menaces sur la réaction aux menaces et sur le SI.

Influence de l'Avatar (Facteurs Externes)

Dans notre deuxième axe, nous nous sommes intéressés à la couche intermédiaire de notre représentation : l'Avatar. Les études explorant l'influence de certains facteurs sur le SI se concentrent généralement sur un facteur à la fois et mesurent son influence sur le SI. Différents facteurs d'influence principalement liés aux choix de conception des avatars ainsi qu'à leurs caractéristiques techniques ont émergé de cette recherche. Cependant, plusieurs préoccupations se font jour concernant les méthodologies utilisées pour évaluer le SI des utilisateurs en RV. Premièrement, ces mesures ne permettent pas d'évaluer les interrelations entre les facteurs qui influencent le SI des utilisateurs. En effet, si nous commençons à mieux comprendre l'influence de facteurs isolés sur le SI, nous avons encore peu d'informations sur la contribution relative de chaque facteur sur le SI, ou sur la préférence de l'utilisateur pour un facteur plutôt qu'un autre lorsqu'il est incarné dans un avatar. Aujourd'hui encore, plusieurs questions restent ouvertes : Y a-t-il une contribution dominante entre les facteurs d'influence du SI? Certains de ces facteurs devraient-ils être privilégiés dans la création d'avatars virtuels ? L'évaluation des interrelations est difficile en termes de protocole expérimental en raison des nombreuses combinaisons possibles de facteurs. Pour cette raison, nous étions intéressés dans cette thèse à explorer de nouvelles façons d'évaluer le SI des utilisateurs, et plus spécifiquement d'une manière qui permettrait l'étude des interrelations au sein des facteurs.

Nous présentons dans le **Chapitre 6**, une étude que nous avons menée pour explorer les interrelations au sein des facteurs du SI. Pour ce faire, nous avons appliqué pour la première fois la technique d'appariement subjectif dans le cadre d'études d'incarnation afin d'explorer la préférence relative entre trois facteurs liés à l'avatar : l'apparence, le contrôle et le point de vue.

Influence de l’Utilisateur (Facteurs Internes)

Enfin, notre troisième axe est consacré à la couche interne de notre représentation de facteurs : l’Utilisateur. Si la plupart des études sur l’incarnation d’avatar ont pu montrer des tendances générales concernant la façon dont les facteurs “externes” semblent influencer le SI, elles n’ont pas pris en compte l’aspect “interne” de l’utilisateur (par exemple, la personnalité ou les expériences personnelles). Toutefois, la variabilité entre utilisateurs reste non négligeable. En pratique, on constate que certains croient facilement à l’illusion de l’incarnation virtuelle, alors que d’autres sont au contraire totalement réfractaires. Les premières recherches sur le lien entre les traits de personnalité et la perception des expériences de RV se sont concentrées sur le sentiment de présence [Wallach et al. 2010]. Par exemple, il a été constaté que l’agréabilité, un trait de personnalité, était positivement associée à la présence spatiale [Sacau et al. 2005]. Plus récemment, certains travaux ont exploré le lien entre les différences individuelles des utilisateurs et le SI. Par exemple, la conscience du corps [David, Fiori, et al. 2014] et les traits de personnalité [Jeunet et al. 2018] ont été étudiés en relation avec le SI. Dans ce dernier cas, Jeunet et al. ont montré que le sentiment d’agentivité était corrélé avec le locus de contrôle, un autre trait de personnalité. Cependant, à part les travaux de Jeunet et al. [2018], la majorité des travaux traitant de ces facteurs internes se sont principalement concentrés sur le SI des utilisateurs dans le monde physique. C’est pourquoi nous avons souhaité étudier plus en profondeur l’influence d’un plus large éventail de traits de personnalité et de la conscience du corps sur le SI en RV.

Dans le **Chapitre 6**, nous visons donc à enrichir les connaissances globales concernant les facteurs influençant le SI en nous concentrant sur les différences individuelles entre les utilisateurs. Nous avons par conséquent exploré l’influence potentielle des traits de personnalité et de la conscience corporelle sur le SI. Ce travail a été réalisé en collaboration avec l’anciennement stagiaire et désormais doctorante Diane Dewez. Ma contribution à cette dernière étude a principalement porté sur les discussions de concepts, la conception expérimentale et, en partie, la rédaction de l’article lié à cette recherche.

UNIVERSITÉ DE RENNES 1

Titre : Contribution à l'Etude des Facteurs Influençant le Sentiment d'Incarnation Envers un Avatar en Réalité Virtuelle

Mot clés : Avatar, réalité virtuelle, sentiment incarnation, expérience utilisateur

Résumé : Le terme “avatar” fait référence à la représentation des utilisateurs dans un monde virtuel, dans le cas où ils portent un casque de réalité virtuelle et ne peuvent donc pas voir leur propre corps. Les avatars sont désormais devenus une exigence majeure dans les applications de réalité virtuelle immersive, ce qui accroît la nécessité de mieux comprendre et identifier les facteurs qui influencent le sentiment d'incarnation d'un utilisateur envers son avatar. Dans cette thèse, nous avons défini trois axes de recherche pour explorer l'influence de plusieurs facteurs sur le sentiment d'incarnation, en nous basant sur une catégorisation qui ne prend pas seulement en compte les facteurs liés à l'avatar, mais aussi les facteurs liés à l'environnement virtuel et à l'utilisateur. En premier lieu, nous avons étudié l'influence des environnements virtuels partagés sur le sentiment d'incarnation, dans une étude où les utilisateurs accomplissaient une tâche ensemble dans le même environnement virtuel, et dans une autre étude où les utilisateurs partageaient le contrôle du même avatar. Dans une deuxième partie, nous avons exploré les interrelations entre les facteurs liés aux avatars qui influencent le sentiment d'incarnation. Enfin, dans une troisième partie, nous avons étudié l'influence des différences individuelles des utilisateurs sur le sentiment d'incarnation.

Title: Contribution to the Study of Factors Influencing the Sense of Embodiment Towards Avatars in Virtual Reality

Keywords: Avatar, virtual reality, sense of embodiment, user study

Abstract: The term “avatar” refers to the representation of users in a virtual world, in the case where they are immersed in Virtual Reality with a Head-Mounted Display and therefore cannot see their own body. Avatars have now become a major requirement in immersive virtual reality applications, increasing the need to better understand and identify the factors that influence users' sense of embodiment towards their avatar. In this thesis, we defined three axes of research to explore the influence of several factors on the sense of embodiment, based on a categorization that did not only consider factors related to the avatar, but also factors related to the virtual environment and the user. In the first part, we have studied the influence of shared virtual environments on the sense of embodiment, in a study where users performed a task together in the same virtual environment, and in another experiment in which users even shared the control of the same avatar. In a second part, we explored interrelations within avatar-related factors influencing the sense of embodiment, using a new methodological approach with a subjective matching technique. Finally, in a third part, we investigated the influence of users' individual differences on the sense of embodiment.