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Diane Dewez

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L'INSTITUT NATIONAL DES
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Par

Diane DEWEZ

Towards Avatar-Based Interaction in Virtual Reality

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“I’ve got so many questions, ain’t got no answer”

Frustration

INTRODUCTION

This thesis entitled “Towards Avatar-Based Interaction in Virtual Reality” investigates interrelations between avatars and interaction in virtual reality (VR). The goal is to better understand how different interaction techniques can impact avatar perception, as well as how the choice of an avatar can affect the interaction technique. In particular, we are specifically interested in how such interrelations can affect the sense of embodiment. The contributions of this thesis will help developers design interaction techniques compatible with full-body realistic avatars.

Avatars and Interaction

Sometimes we like to persuade ourselves that we would be better in some things if we were different. “I would have beaten you in that tennis match if I had more strength!” “I could master this bass line if my little finger could reach this fret!” This is a common belief that talent exists, that we are meant to be good at certain things and not others. But, we are stuck in one body, in one version of our lives, and we cannot really explore alternative versions of ourselves ... in reality. However, thanks to VR, we can actually explore an infinite number of alternative worlds. It is possible to recreate real environments in a controlled and safe manner, or on the contrary to create impossible worlds, for instance where time is controlled by body movement [Hamanishi and Rekimoto 2019]. VR is used in many domains like healthcare, sport training, video games or education. The virtual world replaces the real one by immersing users in the simulated environment and isolating some of their senses. In addition to alternative worlds, we can also explore alternative selves. In VR, it is even better than putting a costume, it actually lets users become shapeshifters. Like the character Mystique in X-Men, users can take any form or appearance they may want. This virtual body, called an avatar, becomes the intermediary between the user and the virtual environment (VE). In this virtual world, where everything can be imagined and defined, users can therefore verify whether they would perform or behave differently in another body. There are various interrelations between the different entities involved (the user, the avatar and the interaction technique) that could influence the results of this

immersion, in terms of body perception, performance or behaviour. As there are already several studies and applications relative to sports in VR, we use the example of a virtual tennis game in this introduction. Each direct interrelation between the different entities is illustrated by a quote from an imaginary user.

Quote 1: “This is just a fake body, it is not my real body!”

First, it is necessary to investigate **the relation between users and their avatar**, to evaluate whether users identify with this virtual body as much as they identify with their real body. VR definitely has advantages compared to desktop video games, as it completely immerses users in terms of sensory information. VR offers new sensory information that can help users feel like they are actually the virtual character representing them. This is possible not only by using visual information, but also additional stimulation such as haptic feedback (tactile and force feedback). Inspired by the rubber-hand illusion (RHI) [Botvinick and Cohen 1998] which gives a synchronous tactile stimulation on a rubber hand and the hidden real hand, thus creating an illusion of owning the rubber hand, the idea emerged to use such visuotactile stimulation in VR [Slater et al. 2008]. This can give the feeling of being the avatar, i.e. a sense of embodiment, even when the avatar has a different age [Tajadura-Jiménez et al. 2017] or a different gender [Slater et al. 2010]. If this sense of embodiment is high, users believe their virtual representation is their real body, then they can act through this avatar. However, it is still not clear whether interacting with this avatar increases or decreases the sense of embodiment.

Quote 2: “It is difficult to accurately control the avatar, I missed the ball because of that.”

Here we focus on **the relation between the avatar perception and the interaction technique, and most specifically the impact of interaction input** first. Transposing an activity like tennis into VR is not an easy task. One of the challenges to do it is for example to correctly track users’ movements. Interaction techniques can use various methods to track users (e.g. controllers, cameras, inertial sensors), which all have their own advantages and drawbacks. Most of them are cumbersome, or still cause tracking losses. Also, will the user hold a real racket, or just a simple controller? All interaction input design choices might have effects on users’ body perception. Indeed, when performing actions, users act through their virtual avatar. Using their avatar to perform actions might change the relationship they have with it. Acting with an avatar uses visuomotor stimulation, and studies showed that this type of stimulation can strongly give

the impression of embodying this avatar [Kokkinara and Slater 2014]. In the nineties, researchers had the opposite opinion that interacting with input devices could on the contrary create a sense of disembodiment, because input devices make users focus on these devices instead of their own body [Davies and Harrison 1996]. In their experience “Osmose”, the authors therefore privileged creating a link between users’ breath and the VE, enabling users to influence the environment by their breath. This gave them a feeling of connecting to this new environment. While this is understandable considering the technical possibilities at that time, this has now evolved and input devices that use directly users’ body are becoming increasingly common (e.g. detecting gestures using controllers and gloves for object manipulation [Hayatpur et al. 2019] or using Kinect to track users’ body for navigation [Dam et al. 2013]). In the current context, it is possible to imagine forms of interaction with the environment that directly use the real body as an input, thus avoiding a disembodiment but on the contrary, creating a sense of embodiment towards the virtual body used for interaction.

Quote 3: “I did not feel the ball hit the racket, I have no idea how strong this shot was.”

Additionally to input devices, **the feedback chosen for interaction may also have an impact on avatar perception**. For example, how can we give users the impression that they really hit a ball with their racket? Several options are possible to make users think that they can feel and act via their virtual body, like having a highly realistic avatar, or touching the environment through this avatar. Computers are not yet powerful enough to provide every type of high quality feedback, such as force feedback and realistic graphics. Choices need to be made, and some factors might have more impact on the perception of users’ virtual body than others. We therefore need to understand how design choices might affect users’ avatar perception. In the future, researchers can converge towards new ways of interacting, compatible with a strong sense of avatar embodiment. However, we also want efficient and easy interaction, and the avatar might impact this.

Quote 4: “Ok I had a more muscular body but the ball did not go fast, so the ball speed is not influenced by my musculature?”

There is still the question of whether **the avatar can have an effect on interaction**, in terms of performance or behaviour. In VR, the way we perceive the environment and act in it differs from the real world. In some cases, the avatar might have an impact, for example it was found that having a virtual body helps resolving puzzles more

quickly [Pan and Steed 2019]. While being embodied in a novel body, people can perceive themselves differently, or even show different behaviours. This is called the “Proteus effect” [Yee and Bailenson 2007], and it starts being investigated in relation to interaction. For example, if we keep the example of the tennis game, it was already found that users can move more if their avatar looks thinner than their opponent’s during a tennis game on Nintendo Wii [Peña et al. 2016]. Another example, if the avatar resembles a stereotype of someone who can play the djembe well, then users’ actual performance can be better than playing with an avatar in a suit, and this performance is correlated with the level of embodiment [Kilteni et al. 2013]. But, sometimes the avatar does not seem to impact interaction, for instance seeing a virtual representation of your hands does not improve your performance in a motor-skill task [Ricca et al. 2020]. Even though avatars offer a spatial reference which helps to perceive the environment [Draper et al. 1996; Mohler et al. 2010], they also sometimes hinder interaction, for example by creating occlusions [Tran et al. 2017]. Avatars are also essential as they are an important clue of what is possible in the VE, they are here to indicate to users what they can perform or not. For example, embodied in a bat [Andreasen et al. 2018], they can potentially fly but they probably cannot grab a 3D object. Considering the environment affordances (the actions offered by an environment) and the avatar’s characteristics (e.g. anthropomorphy, realism, shape, degrees of freedom), users should be able to quickly identify possible actions. Interaction in VR should therefore be designed by thinking about the users’ virtual representation, so that the appearance reveals the possible actions. Avatars can therefore have various and complex effects on interaction, depending on their characteristics, which are still not fully understood.

Motivation and Research Axes

The interest of investigating avatar-based interaction is two-fold. On the one hand, it is linked to this influence of the avatar on interaction, as studies start demonstrating that users would benefit from having better interaction possibilities with a full-body avatar [Kilteni et al. 2013; Banakou et al. 2018]. This impact of having a novel body on users’ behaviour can have great applications in several domains such as education or psychotherapy. For instance, for an application against fear of heights, users could be represented by a flying superhero or a bird avatar. If users manage to easily and efficiently control their avatar and fly with it, this might help them fighting their fear. On the other

hand, it is also linked to the potential contributing effect of interaction on the avatar perception. Having interaction that is compatible with full-body avatars may help to increase embodiment.

While there is therefore a great interest in investigating avatars and interaction together, the knowledge on avatar embodiment and interaction tend to evolve in parallel. There are not many studies investigating the apparent interrelations between both, which could influence the level of embodiment or the way users interact. Nevertheless, the motivations and current challenges to better understand these interrelations are numerous. This thesis aims to extend current knowledge linking the user, the avatar, and the interaction by investigating the interrelations between them. Our work focuses on three main research axes (RA).

RA1: Influence of the user’s characteristics on the sense of embodiment

This axis aims to deepen the understanding of the link between the user and the avatar, i.e. the first interrelation presented with Quote 1. One motivation of this thesis is to better understand how the sense of embodiment is elicited. Even though there is a growing number of studies on the sense of embodiment, it is still a recent research topic in VR and we lack knowledge on how it is elicited. The factors investigated concern mostly the avatar’s characteristics, the type of sensory stimulation or the tracking apparatus. Most studies therefore consider the sample of participants as a whole, without considering inter-individual differences. Yet, body perception is a very personal aspect, and studies often show high standard errors in the participants’ level of embodiment. Researchers do not know yet why some people easily embody virtual bodies, while others seem refractory to the sense of embodiment. As individual characteristics have already been studied in VR for other aspects of user experience such as the sense of presence, it seems interesting to study such individual differences in the context of embodiment. This question will be investigated in Chapter 2 through the evaluation of whether the user’s personality traits can affect embodiment. While this question investigates the unknown effect of the user’s characteristics on avatar perception, it does not take the interaction into account.

RA2: Influence of the interaction technique on the sense of embodiment

This axis corresponds to Quote 2 (for interaction input) and Quote 3 (for interaction feedback), which aims to explore one aspect of the interrelations between interaction and avatar embodiment. Studies on interaction techniques often use interaction-based crite-

ria such as performance or usability. Few studies investigate the sense of embodiment. Nevertheless, in the real world, exploring the environment by interacting with it is a way to know and appropriate our bodies. One component of embodiment is related to the control of the virtual body, which is deeply linked to the possibility of performing actions. When an interaction task is used in a study, it is rarely used as an experimental condition. Therefore, little is known on how the body is perceived depending on the way users interact. Several parameters can change when interacting, such as the input characteristics or the action feedback. The influence of such factors on embodiment needs to be more deeply investigated. This question will be explored in Chapter 3 where we will investigate the impact of locomotion techniques on embodiment, which had not been investigated before. Chapter 4 will focus on manipulation techniques and investigate the impact of a novel type of feedback on embodiment for the specific case of anisomorphic manipulation techniques. Also, contrary to locomotion techniques, there are already several studies on the influence of manipulation on the sense of embodiment. These works can be used to propose new methods of developing techniques more compatible with avatars. In Chapter 5, we will therefore propose design guidelines for manipulation techniques that take avatar embodiment into account.

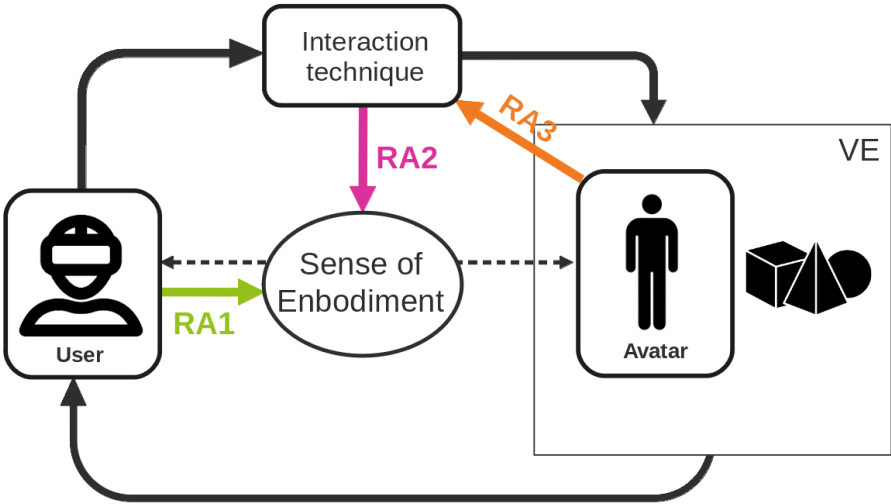


Figure 1 – Illustration of the different research axes, linking the interaction, the user, the avatar, and the sense of embodiment (SoE).

RA3: Influence of the avatar on the interaction

We discussed in the previous section that avatars can sometimes help (e.g. by in-

creasing spatial awareness) or hinder interaction (e.g. by creating occlusions), which was illustrated with Quote 4. The studies investigating such influence of avatars on interaction are recent and still rare, as simpler virtual representations were used when most of the interaction techniques were invented. As a third research axis, we decided to investigate this possible influence of the avatar on interaction more deeply. While Chapter 3 will study the impact of embodying a full-body avatar when navigating, Chapter 4 will focus on manipulation techniques and most specifically anisomorphic manipulation, and how different appearances could impact performance.

Scope and Outline

In this thesis, we investigate two domains relative to VR: interaction and avatar embodiment. We focus on fully immersive VR applications used in Head-Mounted Displays (HMD). We study avatars defined as full bodies or body parts representing users in the VE. The notion of avatar embodiment studied in this thesis is based on the definition by Kilteni et al. [2012a], which may differ from other definitions of embodiment used in the Human-Computer Interaction community for example, where it relates more on the link between interaction and the user's real body. Our work focuses on avatars viewed from a first-person perspective, but related work using third-person perspective will be mentioned. The outline of this thesis will be as follows:

Chapter 1: Related Work on Interrelations Between Avatars and Interaction

We will first introduce related work on avatar embodiment, 3D interaction, and the studies investigating the interrelations between these two domains. While a first part will mostly present the context of this thesis and important aspects of VR, the following sections will develop the notion of embodiment, the impact of avatars on interaction, and the impact of interaction on avatar perception.

Chapter 2: Understanding Individual Differences in the Sense of Embodiment

The second chapter will focus on the sense of embodiment and tackle the question of individual differences in the levels of embodiment. We will present a user study on the influence of personality traits (Big Five traits and locus of control) and body awareness

on the sense of embodiment. 123 participants took part in this study. A two-minute visuomotor task was used to elicit a sense of embodiment towards the avatar. At the end of the experiment, a virtual threat was induced to observe participants' reaction.

Chapter 3: Studying the Interrelation Between Locomotion Techniques and Embodiment

In this chapter, we will explore the impact of interaction on embodiment by focusing on locomotion. We will detail a user study that we conducted exploring the influence of locomotion techniques on the sense of embodiment. Three locomotion techniques were tested: real walking, walking-in-place and head steering. Each participant used only one technique and did the experiment twice, once with a full virtual body, and once with only 3D models of the controllers.

Chapter 4: Investigating Dual Body Representations During Anisomorphic 3D Manipulation

This chapter will focus on another type of interaction, manipulation, and most specifically on anisomorphic manipulation. It aims at investigating the use of a dual virtual representation when distorting users' motion for object manipulation. Two experiments were conducted, respectively investigating two types of motion distortions (amplified motion or decreased motion). Dual body representations with different visual appearances were compared to single body representations.

Chapter 5: Designing Avatar-Friendly 3D Manipulation Techniques: Practical Guidelines

In Chapter 5, we will leverage the knowledge on manipulation techniques and avatars to propose guidelines and leads of future research. We will present these guidelines for designing "avatar-friendly" manipulation techniques compatible with avatars, based on an analysis of existing literature (presented in Chapter 1). These guidelines are classified into three categories: Input Devices, Control and Feedback. These guidelines could help VR developers designing manipulation techniques that take avatars into account.

Chapter 6: Conclusion

Finally, a general conclusion will recall the different contributions as well as draw future research perspectives.

RELATED WORK: INTERRELATIONS BETWEEN AVATARS AND INTERACTION

This chapter presents the related work on the sense of embodiment and interaction in virtual reality. It first introduces the main concepts of this thesis, namely virtual reality, 3D interaction and user experience in virtual environments. Then, it focuses on the sense of embodiment and how it is defined, elicited and measured in virtual reality. Two sections develop the existing interrelations between avatars and interaction. The first one studies the impact of avatars on interaction, while the second one focuses on the impact of interaction design choices on self-avatar perception.

1.1 General Concepts

1.1.1 Virtual Reality

Virtual Reality (VR) is a concept that emerged during the second half of the twentieth century. The term designates a reality that is “virtual”, i.e. “created by computer technology and appearing to exist but not existing in the physical world”¹. This term became popular in the late eighties, but the concept of simulated environments started earlier, for example with the Sensorama simulator created by Morton Heilig [1961], providing various sensory stimulations to simulate a motorcycle ride. Since then, VR hardware has evolved. The concept of VR has been placed at one end of the Milgram’s Reality-Virtuality Continuum [Milgram and Kishino 1994]. On the other end of this continuum, there is the real world. VR is the opposite of the real world, as everything is simulated in it, which creates a whole new artificial world. Between both ends, there is what is commonly called mixed reality, as it is composed of a certain ratio of real elements and virtual/simulated

1. Cambridge University Press. [2021b], *Virtual (n.d.)* In: *Cambridge dictionary*, URL: <https://dictionary.cambridge.org/dictionary/english/virtual> [visited on 03/08/2021].

elements. This continuum has been revisited recently [Skarbez et al. 2021b], as it was mostly focusing on visual displays while VEs can stimulate all users' senses. The new version of the continuum stipulates that perfect VR is currently an unachievable goal, and that most of the current VR applications are actually a part of mixed reality (see Figure 1.1). Several definitions of VR have been proposed. For example, Steuer [1992] proposed a definition after analysing existing definitions: "A virtual reality is defined as a real or simulated environment in which a perceiver experiences telepresence". Here we present another definition, a technical definition, that was proposed in 2003.

Technical definition of Virtual Reality [Arnaldi et al. 2003]

Virtual reality is a scientific and technical field that uses computer science and behavioural interfaces to simulate the behaviour of 3D entities in a virtual world, which interact in real time with each other and with one or more users in pseudo-natural immersion through sensory-motor channels.

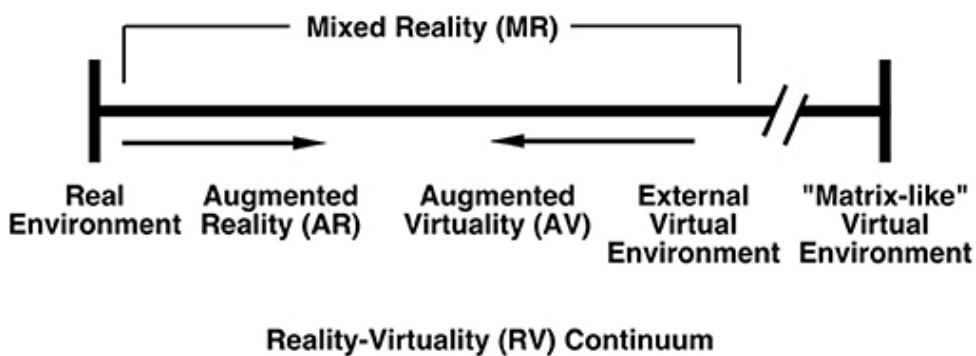


Figure 1.1 – Revisited Milgram’s Reality-Virtuality Continuum by Skarbez et al. [2021b].

VR immerses users in a brand new world, a virtual world. All the components of this world can be controlled by a computer. What users see, hear, touch or smell can be controlled. This opens infinite possibilities, to experience the real world in a safe and customisable manner or to experience unrealistic worlds to stimulate our imagination. To immerse users, there are different apparatus that can be used. In this thesis we will focus on Head-Mounted Displays (HMD). Ivan Sutherland and his team created what is considered as the first HMD in 1968 [Sutherland 1968]. Nowadays, HMD are less cumbersome and can be wireless, letting users move freely. But other types of hardware can be used such

as Cave Automatic Virtual Environment (CAVE), an immersive room made of screens on which the VE is projected [Cruz-Neira et al. 1992].

1.1.2 Interacting with Virtual Environments

In the virtual world, there is the possibility of acting and having influence on the VE, i.e. interacting with the environment. The user is able to perform actions and the environment responds with feedback. The actions that can be performed are in theory all the actions people perform in the real world, like walking, jumping, or grabbing, catching, pinching objects. Many techniques have tried to follow different types of knowledge of the real world, that can be classified using the Reality-based interaction framework [Jacob et al. 2008]. This framework is composed of four categories of real-world knowledge: Naive Physics, Body Awareness & Skills, Environment Awareness & Skills, and Social Awareness & Skills. All techniques using this knowledge form a new generation of interaction techniques after the generation of desktop interfaces. We can also say that this type of interaction offers a high fidelity [McMahan 2011] to the real world, i.e. they imitate the way people interact in the real world. But in VR, people are not limited by real-life physical constraints, so they can have “superpowers”, like reaching remote objects or passing through walls. These superpowers can replace realistic interaction or extend it and offer new functionalities in the virtual world.

Interaction in a VE can be modelised using an action-perception loop (see Figure 1.2). Users’ input can be of various types, e.g. motion, voice, button trigger. It is transmitted to the application via input devices, treated by the environment which gives feedback thanks to output devices. The feedback can be coherent with the input. For example, a user motion can be directly mapped to a similar motion done by the user virtual representation. In this case, we talk about one-to-one mapping, or isomorphic interaction. But sometimes, a transformation is applied to the input to obtain a different feedback, thus creating distorted motion. In this case, we talk about anisomorphic interaction. The gain applied to the input is called a Control-Display gain (CD gain), as the display (feedback) is different from the user control (input). It is the gain applied to the input to compute the position of the displayed representation. It has been studied in the 2D [Casiez et al. 2008] and 3D contexts [Argelaguet and Andujar 2013]. This gain can be constant or adaptive (it varies depending on some conditions). A CD gain lower than one means the displayed motion is smaller than the real motion. A CD gain greater than one means that users’ motion is amplified.

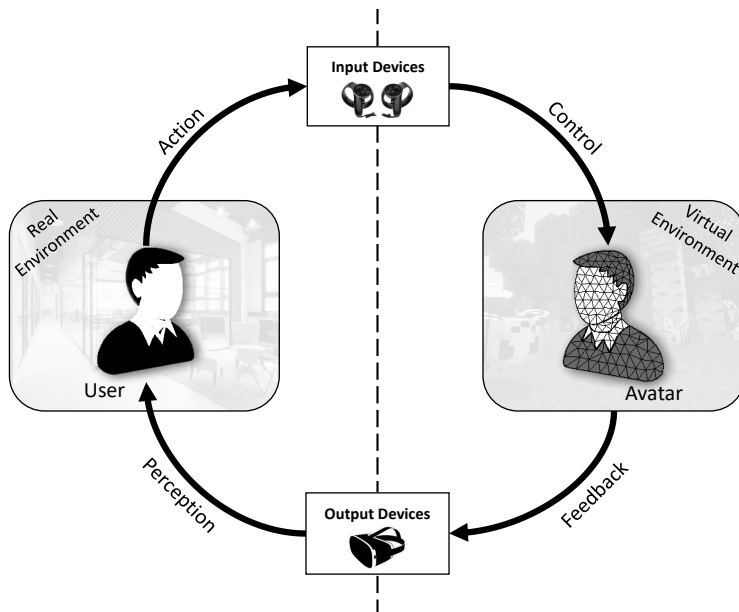


Figure 1.2 – Action-perception loop: the user can control the avatar thanks to the input devices, so as to interact with the VE. In response to the user’s actions, the VE provides feedback perceived by the user thanks to the output devices.

After having processed the input, the VE gives feedback to users. There are various types of feedback that can be given, related to each of the five human senses: visual, auditory, haptic and more rarely olfactory and gustatory. The three first types are the most common to give feedback after an action. They can either confirm the consequences of users’ actions, or just inform of the current state of the application. Without this feedback, users cannot efficiently interact with the VE [Wingrave et al. 2002].

Interaction with the VE can take many forms. One simple and established taxonomy is the one by Bowman [1999] classifying interaction into navigation, selection, manipulation and system input. In the case of navigation, users’ motions result in camera translation and rotation. Selection and manipulation let users choose objects and apply transformations to these objects (translate, rotate or scale them). System input enables users to modify parameters in an application, to access a menu or to write text. In this section, we will present previous work on selection and manipulation, as well as on navigation. We will not focus on system input, as most techniques used for system input are similar to the ones used for selection and manipulation.

1.1.2.1 Selection and Manipulation

Selection and manipulation are either separated or considered as one global type of interaction category. Selection is the action of choosing the object the user will interact with. It is composed of two phases: first, users position the selection tool on the desired target; second, they confirm the selection by clicking on a button for example. Selection techniques vary in terms of selection tools, the most used ones being a virtual hand and a ray. They can be classified using other criteria, for example the provided degrees of freedom [Argelaguet and Andujar 2013]. Manipulation tasks encompass all the modifications that can be done on the selected virtual object. Manipulation is often summed up to four canonical tasks: positioning, rotation, scaling, as well as selection if we consider it as a subcomponent of manipulation [Poupyrev 2000; Bowman et al. 2004]. Numerous manipulation techniques have been proposed in order to cope with the complexity of 3D manipulation [Mendes et al. 2019]. Selection and manipulation can be anisomorphic. The CD gain can be lower than one to provide a higher control for precise positioning [Frees and Kessler 2005]. It can also be greater than one to provide higher speed of manipulation when precision is not crucial, or to reach remote objects [Poupyrev et al. 1996]. Creating distorted motion by modifying the CD gain can also be used to provide haptic feedback, to lead the user to a physical prop [Kohli et al. 2012; Azmandian et al. 2016]. This technique applies an offset to the virtual hand so the user will reach the real tangible object.

1.1.2.2 Locomotion

Locomotion techniques enable users to translate and rotate in the VE. Numerous studies talk about navigation, which is more specific to task involving wayfinding. Locomotion in VR has been widely studied [Al Zayer et al. 2020], and many techniques have been created to tackle the problem of limited physical space, like walking-in-place [Slater et al. 1995] or teleportation [Bozgeyikli et al. 2016]. Some of these techniques use virtual movements (i.e. virtual steering) or physical motions but with lower interaction fidelity (e.g. walking-in-place), i.e. which are not similar to the way people interact in real life [McMahan et al. 2012].

As for manipulation, navigation can be anisomorphic. A CD gain greater than one can be used to travel a longer distance [Interrante et al. 2007] or to increase rotation to reorient the user towards a certain direction [Steinicke et al. 2009].

Several taxonomies have been proposed to classify all the proposed locomotion tech-

niques. The first taxonomies were mainly focused on the implementation aspects, like the velocity selection, the target selection [Bowman et al. 1997]. With the growing mastery of navigation algorithms, the taxonomies have focused more on the paradigms used. Arns et al. [2002] made the distinction between physical and virtual navigation. Another taxonomy has been proposed more recently, separating locomotion techniques into four categories: room-scale-based, motion-based, teleport-based and controller-based [Boletsis 2017]. Nowadays, the tendency is to focus more on the user and its perception of locomotion [Albert and Sung 2018].

1.1.3 Immersion and Presence

There are various user experience criteria in VR, such as enjoyment or comfort. In this section we focus on two aspects that have been extensively explored in the VR literature: immersion and presence. Immersion is the objective level of realistic sensory modalities provided to users [Slater 2003]. It highly depends on the different output devices used, as well as the software part. A highly immersive application provides rich sensory stimulations such as high-quality graphics, sound and touch feedback. As VR immerses users into another alternative world, it can give them the impression of being elsewhere and not in the real world anymore. The feeling of “being there” has been called the sense of presence. Several studies investigated factors influencing the sense of presence. For example, having a virtual body can increase the sense of presence [Slater and Usoh 1993b]. Presence differs from immersion, as it does not solely depend on the apparatus but is a psychological construct in users’ mind, which can vary depending on each individual mental representations. It is a reaction to immersion [Slater 2003] and it makes users react realistically to the virtual world. Slater [2009] introduced two components to substitute the sense of presence: Plausibility (Psi) and Place Illusion (PI). Place Illusion globally corresponds to the previous sense of presence, which gives to users a similar sensation as being in a real place. Plausibility refers to the credibility of the scenario. Plausibility is high if users think the events in the virtual world are really occurring.

This thesis focuses on VR, a simulated world in which users can feel like they are really situated in it and where they can interact. An important element that makes presence higher and make interaction possible is the new virtual body that is given to users.

1.2 Embodying an Avatar

In VR, users have the possibility to be represented by an avatar, i.e. virtual body parts or a full body. They can feel a sense of embodiment towards this avatar, i.e. feel like this avatar is their real body [Kilteni et al. 2012a]. In this section, we will present related work on the sense of embodiment, from its emergence to its measures, its impact on users, and the factors influencing it.

1.2.1 Emergence of Avatars in Computer-Mediated Technologies

With the emergence of computer-mediated technologies and the internet, people started to need ways of expressing themselves to other people online. Because communication through text was highly limited, they also quickly needed a way to show a representation of themselves to other users, to express their identity. It started with profile pictures, usually called avatars, a term that first appeared mostly in video games or novels. This term has been extended to call all types of users' representation in a VE. From video games or chat platforms to VR, these avatars are users' virtual identity. They can be customised and serve as users' proxy in the virtual world. The definition of the word avatar sometimes vary between communities and researchers. A review by Nowak and Fox [2018] on the different uses of the word avatar led to this definition:

Definition of an avatar [Nowak and Fox 2018]

An avatar is a digital representation of a human user that facilitates interaction with other users, entities, or the environment.

An avatar is therefore the means used to interact, with other users but also with the VE. With other users, it lets users communicate through gestures for example. It is essential for social interaction to be able to see other users and know what they are doing. For interaction with the VE, it influences users' capabilities (see Section 1.3.1.1). For example, thanks to their avatar, users can know their position in the virtual world. The avatar also represents how they want to expose themselves to other users in the case of multi-user applications. The chosen appearance can depend on the application context, it reveals both how users want to present themselves to others, and how they perceive

themselves [Vasalou and Joinson 2009]. There is therefore a strong relation between users and their avatar, that has been extensively studied in several communities. Indeed, the question of the relation between users and their avatar is an interdisciplinary question, involving as much the fields of HCI (with the question of embodied interaction), than art or psychology [Hamilton 2009].

1.2.2 The Evolving Concept of the Sense of Embodiment

In VR, this relation between users and their avatar is even stronger. When using HMDs, users' visual sense is reduced to what is visible in the headset. They cannot see their real body anymore, thus being left with only a virtual representation of themselves. As their real body is hidden, people can have the illusion that their avatar becomes their real body. This illusion has been studied in VR since the nineties. First called Illusory Virtual Body Ownership (IVBO), researchers investigating this question now use more often the term sense of embodiment, defined by Kilteni et al. [2012a]. This definition decomposed the sense of embodiment into three subcomponents: the sense of self-location, the sense of agency and the sense of ownership. This proposed structure has the advantage of clearly defining three aspects of embodiment, that represent different criteria of experiencing a body as our own. The sense of ownership was the component already studied in experiments on IVBO. VR is particularly efficient at creating ownership, as other types of media have more difficulty in creating such an illusion that the body is part of our own. There is the idea of a link between the user and the avatar in this component, both on an affective and a sensory aspect: this body is a part of users' body and they receive every stimulation through this body. The sense of agency is related to control. It has been extensively studied in other domains outside VR [Pacherie 2007]. A strong sense of agency implies both identifying yourself as a cause of an action, and experiencing a logical feedback relative to a performed action. Jeunet et al. [2018] differentiated these two aspects by calling them the feeling and judgment of agency, based on previous studies in psychology. Finally, the sense of self-location refers to the spatial location of the avatar relative to the user's actual position. The main factor influencing it is the perspective from which the avatar is seen. The sense of self-location is high when the avatar is seen from a first-person perspective (1PP), and low when seen from a third-person perspective (3PP) [Blanke and Metzinger 2009]. It can be also impacted by tactile stimulations to some extent [Lenggenhager et al. 2009]. This notion of self-location comes from original real-life experiments like the rubber-hand illusion (RHI), where the fake hand and the

real hand were not at the same location. In VR, it is easier to have a co-located avatar when the tracking is correct. Therefore this component has created less interest in the VR community recently. There are still interesting applications in VR that can disrupt this sense, for example out-of-body experiences where the user can be placed outside the virtual body on purpose [Bourdin et al. 2017].

While this structure has established a common reference to all researchers in the domain, the knowledge on the sense of embodiment in VR is still limited and definitions may need to evolve in the future.

1.2.3 Measuring Embodiment in Virtual Reality

The research on subjective measures to the sense of embodiment has highlighted the complex interrelations between all aspects covering embodiment, and the difficulty to clearly separate them [Roth and Latoschik 2020; Peck and Gonzalez-Franco 2021]. These subjective measures often take the form of a questionnaire. Items were first inspired from questions asked for the RHI. They have evolved with the experiments becoming more and more complex, and introducing more factors and types of feedback. Nowadays there are questions on the tactile sensations for example [Peck and Gonzalez-Franco 2021]. Researchers also tried to identify objective measures that could be correlated to the sense of embodiment. As in the RHI [Ehrsson et al. 2007], a threat introduced to the fake body can create a reaction if the user felt embodied. The reaction can be evaluated with physiological measures such as skin conductance response [Armel et al. 2003]. This reaction is a behaviour that was found correlated to the sense of embodiment [Yuan and Steed 2010; Zhang and Hommel 2016]. Other behavioural responses can be used as additional clues of embodiment, for example voice frequency [Tajadura-Jiménez et al. 2017] or movements [Kilteni et al. 2013]. Behaviour can show how much users identify with the character representing them.

1.2.4 Behavioural Impact of the Sense of Embodiment

These changes in behaviour and reactions are a consequence of embodying a different body. Embodiment is a powerful illusion that can have surprising cognitive effects. For example, embodying an avatar with a different skin colour can reduce implicit racial bias [Banakou et al. 2016]. The avatar characteristics can influence users' thoughts and behaviour, they can start acting as someone with their avatars' characteristics would. This

is called the Proteus effect [Yee and Bailenson 2007]. People embodied in a child avatar can start talking with a higher pitch [Banakou and Slater 2014]. It can also influence users' cognitive performance when they embody an avatar looking like Einstein, and this effect is even higher for people with a low self esteem [Banakou et al. 2018]. Another study found contradictory results, with no effect of being Einstein on cognitive performance, but an impact of the appearance of another user in the VE [Kocur et al. 2020b]. If the other user looks like Einstein, there is an increase in the cognitive performance, that may be due to a competitive behaviour. This is not a simple process and might depend on the context. Contrary to the study on cognitive performances, a study found that an avatar that looks like an artist decreases creativity compared to a look-alike avatar [Rooij et al. 2017]. Embodying an avatar is not only about experiencing a novel appearance, it can sometimes have an impact on users' cognition.

1.2.5 Impact on Body Image and Body Schema

The illusion created by the sense of embodiment is related to users' own body perception. Everyone has their own mental self-representation. One common theory, the dyadic taxonomy, says that people have at least two mental body representations, generally called body image and body schema [Gallagher 1986]. The body schema "consists in sensorimotor representations of the body that guide actions" [De Vignemont 2010]. Contrary to body schema which does not exist apart from the environment, body image is "a conscious image or representation [...] differentiated from its environment" [Gallagher 1986]. De Vignemont [2010] stated that body image "groups all the other representations about the body that are not used for action, whether they are perceptual, conceptual or emotional". Embodying an avatar challenges users' mental representations of themselves. For Biocca [1997], a duel takes place in the virtual world between the physical body and the virtual body, to alter body schema. The avatar appearance can alter mental representations, but also acting through this avatar. Similarly as tools can impact body schema [Maravita and Iriki 2004], interacting through an avatar that has a different morphology like a three-arm avatar for example [Laha et al. 2016] can alter body schema (see Figure 1.3). Proprioceptive drift is one possible alteration of the body schema. This drift happens for example in the context of the RHI, where the real hand drifts towards the fake hand. In VR, such drift has also been observed for example with a long-arm illusion [Kilteni et al. 2012b]. When displaying a long virtual arm, participants experience a shape modification of their mental representation and feel like their real hand shifts

towards the remote virtual hand. However in this study, proprioceptive drifts and ownership were not correlated, showing possible different underlying processes. It was also found that a remote virtual hand alters body schema especially when participants feel a sense of agency towards this virtual hand [D'Angelo et al. 2018]. This sense of agency appears when the virtual hand movements are synchronous with the participants' ones.

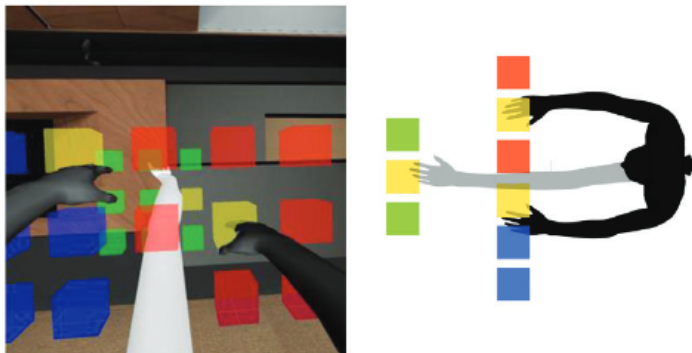


Figure 1.3 – Control of an avatar with a different morphology, for example an avatar with a third arm. Image from [Laha et al. 2016].

1.2.6 Factors Influencing the Sense of Embodiment

VR enables the full control of a wide number of experimental factors, from the stimulation protocol to the appearance and morphology of users' avatar, which has resulted in a notable body of literature examining the impact of such factors on the perceived sense of embodiment. These factors can be: top-down factors, i.e. depending on users' mental representations and cognitive processes that can moderate the influence of stimulations; or, bottom-up factors, i.e. depending on the provided stimulations detected by sensory organs [Kilteni et al. 2012a]. Here we prefer a classification by external factors, depending on the VE and the avatar, and internal factors, depending on the user [Fribourg 2020]. This classification clearly separates controllable factors from factors solely depending on users.

1.2.6.1 External Factors

At the origin of virtual embodiment, there are real-world embodiment illusions such as the RHI [Botvinick and Cohen 1998]. In this experiment, a touch visually applied on a rubber hand that is synchronous with an experienced touch on the real participant's

hand can give the illusion of owning the rubber hand. The central idea in this illusion is to deceive the brain by creating a plausible stimulation. The result of an event (a motion, a touch) must be logical in reaction to the initial event. Progressively this illusion was transposed to VR. First, IJsselsteijn et al. [2006] reproduced the RHI by projecting either the real hand or both the hand and the stimulation (with a paintbrush). A few years later, an experiment was conducted that created an illusion of owning a virtual hand, with results as strong as the RHI [Slater et al. 2008]. In this experiment, they used a hand-held “Wand” device, with a ball attached to it (see Figure 1.4). There was a similar virtual ball touching the virtual hand.

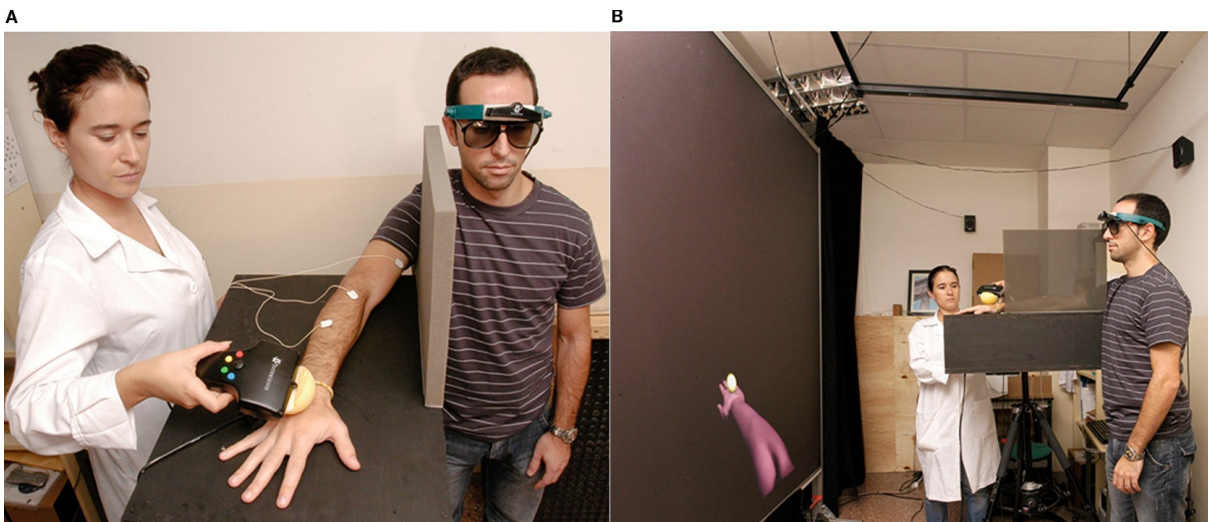


Figure 1.4 – First experiment in VR using visuotactile stimulation to elicit a sense of embodiment towards a virtual arm. Image from [Slater et al. 2008].

In parallel, there were also studies focused not solely on the hand but on the full body. These studies started by the experiment of Petkova and Ehrsson [2008] inducing the illusion of owning a manikin body seen from a first-person perspective in a video feed. This experiment used a visuotactile paintbrush stimulation like in the RHI. A similar experiment was conducted in which subjects could see a virtual projection of either their real body or a fake body from a third-person perspective [Lenggenhager et al. 2007]. Most of these studies therefore used a visuotactile stimulation, i.e. they used an object (paintbrush, ball) to touch users’ real body at the same time as the object virtual counterpart touched the virtual body. But this is not the only way to induce a sense of embodiment. The second main means to induce it is a visuomotor stimulation. In the real world, the RHI was conducted using a moving rubber hand following participants’ real hand move-

ments [Kalckert and Ehrsson 2012] and with a projection of the real moving hand [Tsakiris et al. 2006]. The same method can be used in VR, by making the avatar reproduce users' movements [Kokkinara and Slater 2014].

While visuotactile and visuomotor stimulations are the two main means of creating an embodiment illusion, there were also experiments reporting the illusion by using only a visuoproprioception stimulation, i.e. by only showing a virtual body where users' real body was located. If the virtual body was co-located with the real body and had a realistic skin tone, this was enough for the illusion to appear [Maselli and Slater 2013].

Visuomotor stimulation is currently the most used type of stimulation. It was found to be stronger than visuotactile stimulation [Kokkinara and Slater 2014]. This is to our advantage because the goal of the avatar is not to be solely observed by users, but also used to perform actions with the VE. If users perform movements in the VE, and that their avatar follows their movements, it is therefore possible to create a sense of embodiment. A recent study also found that visuomotor stimulation provokes a disembodiment faster than visuotactile stimulation [Lesur et al. 2020]. Tracking must therefore work well, as mismatches might decrease embodiment more quickly when using visuomotor stimulation. Spatial and temporal synchrony are extremely important, especially for the sense of agency [Jeunet et al. 2018]. While users can still feel in control when the offset between the action and the feedback is slightly manipulated, the sense of agency is however lost when the visual feedback becomes too obviously asynchronous [Debarba et al. 2018].

In addition to external factors concerning the type of stimulation, other factors were also found to affect the sense of embodiment, such as avatar appearance. Despite the fact that it is possible to feel some ownership when seeing only virtual hands and feet [Kondo et al. 2018], the avatar appearance has been shown to be of importance to maximise the ownership illusion. For example, it is usually stronger with an avatar with coherent clothes or skin tone [Maselli and Slater 2013], and potentially even higher with a personalised avatar or a self-representation [Waltemate et al. 2018; Gorisse et al. 2019]. The sense of agency is less sensible to appearance. It can be elicited even with point-line avatars [Wellerdiek et al. 2013] and with virtual limbs in implausible positions [Tsakiris et al. 2006].

1.2.6.2 Internal Factors

External factors focus on different experimental conditions (e.g. stimulation, appearance, perspective), yet, they rarely consider individual differences. These individual differ-

ences can be due to internal factors depending on users. While there are not many studies investigating the influence of such factors on embodiment, their influence has been more explored in studies on the sense of presence [Slater and Usoh 1993a]. In particular, personality 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. For example, it was found that agreeableness was positively associated with spatial presence [Sacau et al. 2005]. 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 [Bernstein and Putnam 1987]). 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] 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 was also demonstrated to have an influence on the sense of presence. People with an internal locus believe they are in control of events, while people with an external locus believe in external influences (e.g. fate). 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.

For the sense of embodiment, some internal factors such as body awareness [David et al. 2014] and personality traits [Jeunet et al. 2018] have been studied. However, the majority of the works addressing such internal factors 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 investigated but no correlation was found with the strength of the RHI [David et al. 2014]. Regarding personality and RHI, it has been found

that the illusion is stronger for empathic people [Asai et al. 2011; Seiryte and Rusconi 2015]. The sense of ownership in the RHI was also found 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 in 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 shows both a clear interest and important results regarding the influence of personality on users' sense of embodiment in the physical world. Some more recent work also revealed an influence of the locus of control, a personality trait, on the sense of embodiment in VR. This last result highlighted the potential role of individual differences in the elicitation of the sense of embodiment in VR and in this way, raised the concern of exploring deeper their possible link with the sense of embodiment in VR. **For this reason, a part of this thesis (see Chapter 2) will explore this matter by investigating the potential effect of personality traits and body awareness, which are two factors varying from one person to another that can be linked to embodiment.**

1.3 The Impact of Having a Virtual Body During Interaction

In real life, the body is the means of performing actions through our motor system, and of receiving feedback through our sensory system. In VR, the avatar serves as the intermediary between the real body and the VE. It shows actions performed by users and can visually receive a feedback, as the user would receive in the real world. As we said before, there are various avatars possible, and the avatar chosen in an application can impact the way users interact.

First, an avatar affects users' perception of their capabilities and of the environment. It can also affect their perception of their own movements, even when these movements are distorted in the VE. These effects also highly depend on the coherency between the avatar and the input modality used. Finally, the avatar chosen can also impact performance, depending on the task.

1.3.1 Impact on Perception of Interaction Capabilities and Environment

1.3.1.1 Affordances and Environment Perception

In real life, people learn progressively which tasks they are able to do or not. From the youngest age, people learn that their hands can grab objects, but also where an object should be grabbed depending on its shape and centre of gravity. Legs can let humans walk, or step over obstacles. Arms have a limited length that do not let people grab remote objects. People use the perception of their own body to know what is feasible. In 1979, Gibson’s ecological approach introduced this idea of a strong link between the environment and the human perception system [Gibson 1979]. People perceive what actions the environment offers by considering their own body abilities. In the VE, users also perceive the affordances of the environment, i.e. “the use or purpose that a thing can have, that people notice as part of the way they see or experience it”² by taking their body into account. There are some affordances from the real world, when users can interact with some objects as they would in real life. There are also unrealistic affordances, such as superpowers offered by VR like the World-in-Miniature technique [Stoakley et al. 1995], a miniaturised version of the environment that lets users move objects in this environment. Developers must be careful about affordances and design choices, as they must guide users and show them what actions are feasible or not. Users’ avatar can give clues as to what is possible or not [Seinfeld et al. 2020a]. For example, the degrees of freedom offered by the avatar can limit the interaction. If users are represented by a sphere, they know they can probably translate this representation, maybe select objects by clicking on a button for example, but they will not be able to perform precise hand poses to grab objects. Also, depending on the hand appearance, people can have the impression of having a better tactile sensitivity [Schwind et al. 2018a]. The avatar, in relation to the affordances offered by the environment, tells users what they can probably do or not. It is similar to 2D desktop applications, where a cursor on a text indicates that it can be placed somewhere to add/delete some characters, or a hand cursor implies that users can drag and drop. Avatars can also be used to show extended abilities. For example, an avatar with an extendable arm can imply that users can reach remote objects [Feuchtner and Müller 2017].

2. Cambridge University Press. [2021a], *Affordance (n.d.) In: Cambridge dictionary*, URL: <https://dictionary.cambridge.org/dictionary/english/affordance> [visited on 03/08/2021].

Also, similarly to real life [Hall 1966], the virtual body serves as a reference frame to interact with the environment. It is even more essential in VR, as users tend to show a size and distance perception bias, usually underestimating distances and object size [Plumert et al. 2005]. It has been demonstrated that displaying an avatar can improve these perceptions [Mohler et al. 2010]. In a multi-user application, the virtual body helps to understand the VE scale, but the other users' size can have more impact, especially if there are lots of users [Langbehn et al. 2016]. McManus et al. [2011] did not find an effect of a self avatar on distance estimation, contrary to previous works. They hypothesise that this is due to participants seeing their avatar in a mirror, which potentially decreased their sense of embodiment (because of visual differences), thus lowering the impact of cues provided by the avatar.

The avatar can also help users decide whether they can perform an action. Lin et al. [2012] showed that the presence of an avatar changed users' perception of being able to step over a pole, but had no significant influence on their decision to pass through a doorway, as recently confirmed by Bhargava et al. [2020]. However, the choice of rotating shoulders to pass an aperture and avoid collisions was found influenced by the presence of an avatar [Mestre et al. 2016]. Similarly, the avatar's gender can also have an influence on affordances, in particular in collaborative VEs. Buck et al. [2019] studied two-person joint actions while passing through apertures, and found an effect of avatar's gender on participants' behaviour. However, these behaviours are a bit different and more complex than the ones observed in real-life.

For manipulation tasks, it was found that hands with a personalised size increase the correct estimation of object size [Jung et al. 2018], and that this effect can also depend on the realism of the avatar's appearance [Ogawa et al. 2018]. This is coherent with early results showing individual differences during manipulation of virtual objects and the importance of calibrating the experience for each individual [Wang et al. 1997]. Similarly, virtual foot size can influence affordance and environment perception. Having enlarged virtual feet affects both judgment of stepping over and estimation of the width of a virtual gap [Jun et al. 2015]. For tasks involving full-body motions, the avatar also helps to estimate users' height compared to different types of obstacles. For example, having a full virtual body helps users know whether they can step off a ledge or pass under a pole [Bodenheimer and Fu 2015]. In this between-subjects study, they tried three virtual representations: no avatar, line avatar and full-body gender-matched avatar. They found a significant difference between the no avatar condition and both line and full-body avatar,

with people having more difficulties to estimate their abilities without an avatar. The fact that there was no significant different between line and full-body avatars supposes that avatar realism is not very important for affordance judgment, in the case of stepping off a ledge.

1.3.1.2 Visual Occlusions

Occlusions often serve as a depth cue, helping people compare depth between objects [Ono et al. 1988]. However, the avatar can occlude virtual objects and therefore hinder interaction. The more body parts are represented, the higher the risk of this occurring. This can prove critical in applications providing only visual feedback contrary to real life, where other types of feedback (haptic, auditory) can prevent people from being bothered by occlusions. For example, a study found that users perform better with a virtual hand than with a virtual whole arm [Tran et al. 2017]. The authors hypothesised that this is due to the whole arm hiding the scene more and creating occlusions. This is also consistent with the study by Argelaguet et al. [2016], where users performed better with skeleton hands than with realistic hands which generate more occlusions (see Figure 1.5).

In order to minimize occlusions, some potential solutions have been considered. For example, the avatar’s hands can become transparent [Zhai et al. 1994; Buchmann et al. 2005] when users approach a virtual object. This maintains an anthropomorphic representation of the user while keeping the virtual object visible through this representation. Providing additional feedback of the object hidden by the avatar (e.g. with a supplementary view from another perspective) [Bichlmeier et al. 2009] is also an alternative. The latter has the advantage of not changing the appearance of the avatar at the exchange of higher task complexity.

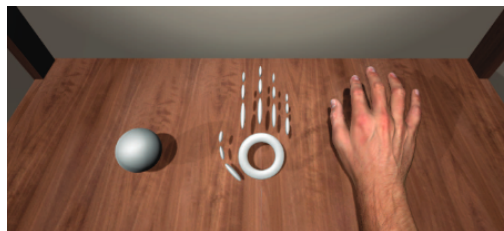


Figure 1.5 – Examples of different possible hand appearances for a manipulation task. Image from [Argelaguet et al. 2016].

1.3.2 Impact on Perception of Distorted Motion

Thanks to the avatar, it is possible that users do not notice motion distortion. Users' visual perception dominates proprioception [Burns et al. 2005], making this illusion possible. For example, even if users perform a small movement in real life, if their avatar moves a lot, they will trust the visual feedback more and think that they performed a larger movement. Several studies investigated the thresholds beyond which users notice this modification of their movements. It was found that displaying a realistic hand instead of a spherical cursor increases the detection thresholds during remapped movements by more than 30% [Ogawa et al. 2020a]. When reaching for an object, participants did not detect the horizontal shift applied to their movement as much in the realistic hand condition as in the spherical cursor condition (see illustration in Figure 1.6).

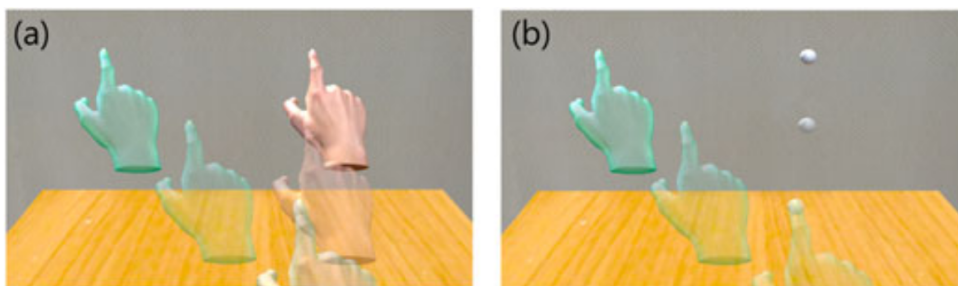


Figure 1.6 – The participant is represented by either a realistic hand (on the left image) or a spherical pointer (on the right). The transparent hand represents the user's real hand, not displayed in the VE. Image from [Ogawa et al. 2020a].

Another study found that the subjects who felt a sense of ownership towards their avatar tended to detect distorted motion less [Burin et al. 2019]. A study by Bourdin et al. [2019] found that it is possible to impact muscular activity by altering avatar's motion, without users noticing. The task used was flexing the elbow to an angle of 90° , with an elastic band. The virtual arm was flexed by either the same angle, 75° or 105° . The sense of ownership and agency were not impacted by the distortion. While the avatar seems to help increasing detection thresholds for manipulation tasks, it was found that displaying feet during redirected walking does not impact sensitivity to translation gains [Kruse et al. 2018]. Similarly, no significant result was found by Reimer et al. [2020] when using a full-body representation. There was also no significant effect of virtual representation on detection threshold in a study on redirected jumping [Li et al. 2021]. The presence of an avatar therefore seems to have less impact on whole body movements.

1.3.3 Coherency between Avatars and Input Devices Can Influence Interaction

There is a strong relationship between the chosen user representation and the input device used [Seinfeld et al. 2020a], e.g. it is rare to use hand tracking to control a simple sphere cursor. The user representation can also impact the way users hold the input device, how they manipulate objects [Kadri et al. 2007], as well as their preferred input device. For instance, previous work demonstrated that users prefer hand tracking to controllers when represented by realistic virtual hands because it is more realistic and fun [Moehring and Froehlich 2011; Lin et al. 2019]. However, designers usually choose controllers in most applications, probably because they are more reliable, accurate [Moehring and Froehlich 2011] and commonplace. Various types of controllers exist, differing in terms of shape, buttons and other inputs available, weight or haptic feedback provided. It is questionable whether the way they are displayed in the VE should be generic or not. Using controllers therefore raises several questions: When using such controllers for interaction, what user representation should be chosen? But also, how does this choice impact the interaction performance? With most controllers, a virtual hand can be used as a generic representation that would directly manipulate virtual objects. In 1999, Bowman [1999] recommended the use of virtual hands rather than virtual tools like raycasting to ensure efficient positioning and rotation of virtual objects. In this case, the different discrete inputs (buttons on the controllers) can launch actions such as grabbing of virtual objects, a solution often used in current VR applications. But sometimes, the controller used is inspired by a real tool and specific to an application, especially in training applications. In this case, it might be preferred to display the 3D model of this tool in the avatar’s hand, to provide realism and coherency with the haptic feedback provided by the input device [Insko 2001]. Using virtual tools in the same manner that we use real tools has the advantage that it is straightforward. Moreover, using virtual tools was found to activate the same regions in the brain as real tools [Rallis et al. 2018], which highlights that virtual tools are treated behaviorally by the brain in a similar manner to physical tools. Displaying virtual tools instead of hands can also be an explicit cue for possible actions in the VE [Seinfeld et al. 2020a]. Choosing a virtual hand or a virtual tool in the avatar’s hand as the representation of an input device can therefore change the way the user’s interact.

1.3.4 Impact on Performance

As seen in Section 1.3.1.1, the avatar helps users during interaction by providing spatial awareness [Draper et al. 1996] and perceive their capabilities correctly. This can increase performance. When navigating, a realistic self-avatar can help having smoother trajectories and avoid collisions [Medeiros et al. 2018]. McManus et al. [2011] investigated the influence of a self-avatar on two types of interaction: grabbing and placing precisely a stamp tool, and a stepping stone task. They found that the avatar helped to increase performance, but not more than seeing an animated character perform the task. Additionally, avatar appearance can vary in terms of shape, size or texture, which can influence interaction. The more complex the representation, the more information users can obtain to potentially improve their performance. For instance, people perform better in a bow-shooting task with a full-body, and tend to prefer this representation over other simpler representations (only controllers or floating hands) [Gao et al. 2020]. It was also found that people can solve a puzzle more quickly with an avatar than without, but there was no difference between the conditions with feet tracking and without [Pan and Steed 2019]. Another study found a user preference for performing a tool-based pick and place task with a visual hand representation, albeit performance was similar to the condition of performing the same task without a visual hand representation [Ricca et al. 2020]. Similarly, after a two-week training, there was still no significant difference in the motor task performance between a group with a virtual hand representation, and without [Ricca et al. 2021]. The importance of viewing a full virtual body also depends on the task. Pastel et al. [2020] found that the level of body parts visible had no influence on the performance during a grasping task, while seeing a full body led to higher accuracy in a throwing task. In terms of realism, a visually faithful avatar does not outperform a generic avatar in a cognitive manipulation task [Lok et al. 2003] or a robot avatar in a pointing task [Schwind et al. 2018b], showing a potential low impact of human-likeness on performance. Apart from the avatar shape itself (arm length, number of limbs, anthropomorphic or abstract), the appearance can also conscientiously or not imply users' capabilities. For example, stereotypes can impact the way users interact, because they will unconsciously want to interact the way their avatar would, due to the Proteus effect (see Section 1.2.4). For instance, a user plays drums better when represented by a dark-skinned avatar with casual clothes than a light-skinned avatar with fancy clothes [Kilteni et al. 2013] (see illustration in Figure 1.7). This effect can also appear when users compare their own appearance relatively to others' appearance. For instance, when playing virtual tennis on a Wii con-

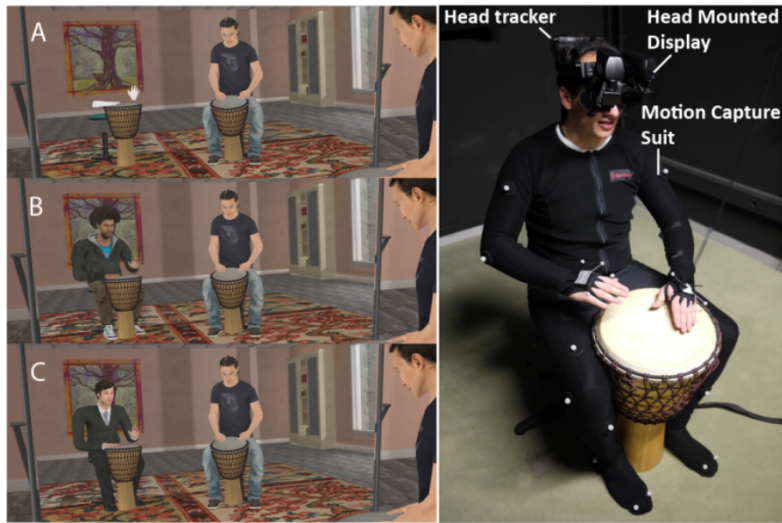


Figure 1.7 – Illustration from the experiment investigating the impact of avatar appearance on the way users drum in VR. Participants are represented either by flat shaded white hands (A), a dark-skinned avatar with casual clothes (B), or a light-skinned avatar with fancy clothes (C). Image from [Kilteni et al. 2013].

sole, users will tend to decrease their physical activity when they perceive their avatar as more obese than the opponent [Peña et al. 2016]. A self avatar’s musculature can also impact performance, as it was found that embodying an avatar with a muscular appearance decreases perceived exertion during an isometric force task [Kocur et al. 2020a].

1.4 The Impact of Interaction Design on the Sense of Embodiment

The avatar can have an impact on interaction as seen in the previous section, but it is also true the other way around. There is a strong link between the interaction technique and the avatar. First, the avatar appearance is linked to the technique, as not all appearances can be controlled by every types of input devices for example, but also because the appearance shows the possible interaction (see Section 1.3.1.1). Second, the avatar is the proxy through which the user can interact, so the user controls the avatar that then interacts with the environment. To do so, users make the avatar move through their own actions. Their actions and the avatar ones must be coherent. As we saw previously (see Section 1.2.6.1), visuomotor stimulation is one of the main way to elicit a sense of embodiment towards a virtual body. As soon as users perform motions that are repercutated

on their virtual representation, they can feel that this representation is their own body. This therefore seems logical that performing different types of interaction in the VE can affect embodiment. Nevertheless, this impact has not been deeply explored. Most studies on embodiment involving visuomotor stimulation used simple actions to perform, such as moving in front of a mirror [Waltemate et al. 2018]. Several studies used interaction tasks: navigation tasks [Medeiros et al. 2018], manipulation tasks [Lin et al. 2019] or a mix of both [Pan and Steed 2019]; but, these studies have not deeply investigated the impact of the task itself on embodiment. Recent studies started to explore factors influencing the sense of embodiment depending on the task performed [Fribourg et al. 2020a], which showed that factors having the highest influence on embodiment seem to be impacted by the type of task. For example, avatar appearance was found to be more important for users in a punching task than in other tasks less focused on upper limbs, like walking or kicking a soccer ball.

In this section, we review the current work on embodiment and interaction. The analysis is decoupled considering the three main design choices for an interaction technique: the input characteristics, the control mechanism and the feedback. The focus is mostly on manipulation techniques as most of studies explored this type of techniques, but we will also mention works on other interaction tasks.

1.4.1 Impact of Input Characteristics

Numerous input devices exist, varying for instance in shape, Degrees of Freedom (DoF), input modality and input interfaces (e.g. buttons, joysticks). If the user has a virtual representation, it means the input device must ensure all possible interaction with the VE but also the control of his/her virtual representation. While the input device is usually the same for both avatar control and interaction such as the case of the virtual hand metaphor, hybrid methods are beginning to emerge using different input devices for avatar control and object manipulation (e.g. hand tracking for hands control and a tablet for manipulation [Surale et al. 2019]).

1.4.1.1 Shape

Controllers have various shapes, but most of them are held in a power grip. When the shape resembles a real tool, this provides high interaction fidelity. Input devices adapted to the task can give better performances [Pham and Stuerzlinger 2019; Bhargava et al. 2018],

as the way the user holds them is more coherent with the task to perform [Batmaz et al. 2020]. Little work exists regarding the influence of device shape on embodiment, probably due to the various types of controllers and its potential low impact. However, there could be an impact of the shape on embodiment, especially depending on the associated virtual model. Depending on the way users hold a device, it can change the way they control their representation and manipulate objects, which can make them feel more or less in control. In particular, this may impact their perception of their avatar if the manipulation is not intuitive. More importantly, depending on the shape, it is crucial to choose an adequate mapping between the controller and the actions performed in the VE.

1.4.1.2 DoF

For most manipulation techniques, the virtual hands are the tool to interact with the virtual objects, except when there is a use of an intermediary element like the ray in raycasting techniques. When using a virtual hand, the DoF provided by the input device are used mostly to control this hand. Intuitively, we can think that the more DoF provided for hand control, the higher the level of control and the sense of embodiment. Supporting this theory, hand tracking was found to elicit a higher sense of ownership than controllers, probably because it provides a finer control of the users' virtual hand [Lin et al. 2019] (see Figure 1.8).



Figure 1.8 – Two different input modalities: hand tracking versus controllers. Hand tracking is preferred and better for the sense of embodiment. Image from [Lin et al. 2019].

However, this effect can also depend on the DoF provided by the user representation compared to the DoF provided by the input device. For example, while Argelaguet et al. [2016] found that agency was better with unrealistic hands (sphere and skeleton hand,

so with limited DoF) using Leap Motion, Lougiakis et al. [2020] found no difference between different hand appearances with a similar protocol using controllers. A potential explanation for this could be that controllers offer less DoF and thus reduce expectations in terms of hand control. The more DoF are provided by the input device, the more control users want during manipulation, especially when realistic representations are used [Argelaguet et al. 2016]. These results suggest that more research should be done on combinations of different input devices and avatars during 3D manipulation.

1.4.1.3 Input Modality and Interaction Fidelity

There are many ways to track users' input. Some apparatus are external to users, like camera-based tracking, while others must be attached to users, or held. For users' hand tracking, two main input modalities could be considered: full-hand tracking and controllers. While controllers are efficient and commonly used, manipulating objects directly with the hands remains the most realistic way both of interacting and of controlling the avatar. It allows fine manipulation as well as direct control of the virtual hand. This is possible thanks to optical devices (Leap Motion, Kinect) or wearables (mostly gloves). However, it implies having precise and robust finger tracking. As previously discussed, in theory hand tracking offers more DoF and therefore better control and probably a higher embodiment [Lin et al. 2019].

However, imperfect tracking can cause mismatches between the visual display and the users' real actions. When the hand movements are constrained by the controllers, there are fewer chances for users to notice mismatches with their real hands. Experiments in which finger tracking provides a good sense of embodiment are usually constrained experiments, for example requiring participants to keep their palm facing down [Hoyet et al. 2016]. Therefore, constraining movements could be one possible solution. Recent input devices (e.g. Oculus Touch, Valve Index) use capacitive sensors for the fingers, providing a good trade-off between offering the efficient tracking of a controller and more precise finger movements for manipulating objects. It would also be interesting to study the impact of hybrid input [Huang et al. 2020] (using both a controller and hand tracking) on the sense of embodiment.

In addition to reliability, controllers also often offer buttons as input, which can be useful to trigger actions in the environment and feel in control, instead of for example launching an automatic animation of grabbing an object when the hand is near it. Using buttons offer low-fidelity interaction, but this can be better in terms of performance

and acceptance than moderate-fidelity solutions [McMahan et al. 2016]. The level of interaction fidelity does not always impact embodiment. For example, when performing a transition between two virtual scenes, techniques with a higher fidelity like turning on yourself or putting a virtual HMD was not found to elicit a higher sense of ownership than a simulated blink metaphor [Oberdörfer et al. 2018]. This study therefore investigated the case of a teleportation from one VE to another, but continuous navigation has not been investigated yet. **To our knowledge, no study investigated the impact of locomotion techniques on the sense of embodiment. This question will be explored in an axis of this thesis (see Chapter 3).**

The best scenario generally remains the high-fidelity case, where the user performs the entire action like in the real world, as a complete control of the avatar elicits a higher sense of embodiment than just triggering actions [Fribourg et al. 2020a]. An alternative form of input is brain signals. Work on Brain-Computer Interfaces (BCI) for precise control is still at its early stage. For the moment, it has been mostly studied for controlling walking [Luu et al. 2016; Alchalabi et al. 2021]. It was already found that BCI can elicit a higher sense of embodiment when making an avatar walk, than finger movements [Cohen et al. 2014].

More important than the input modality itself, what matters is the mapping applied to this input.

1.4.2 Impact of Control and Mapping

A great part of interaction techniques do not consider a one-to-one mapping between input motion and the resulting virtual motion. For example, modifications of the CD gain or constrained motions are commonplace in order to increase the precision of free-hand manipulation, or to redirect users in the VE. However, such control mechanisms can introduce mismatches between the actions performed by the user and the motions of their avatar. As visuomotor coherency is one of the major inducers of the sense of embodiment [Kokkinara and Slater 2014], such changes in control could have a negative impact in the overall sense of embodiment.

1.4.2.1 Motion and Interaction Constraints

Constraints can be used to interact more quickly or respect real world physics. Most constraints applied during interaction are meant to avoid collisions, or to reduce DoF (limit the interaction to a particular surface or an axis for example). When constraining the in-

teraction, it means that the avatar's motion is also constrained, which can create a visual-proprioceptive mismatch and disturb the senses of agency and self-location [Pritchard et al. 2016]. First, several studies decided to handle collisions as it might seem a good idea to create a realistic environment that respect the laws of physics. For instance, when moving an object on a table, it is possible to apply semantic constraints based on real-life physics, as long as the motion of the user is coherent with this constraint (e.g. a horizontal motion on the surface of a table). However, especially for wide and fast motion, blocking the avatar outside objects can create huge offsets between the real hand and its virtual counterpart. This could cause a break in the sense of self-location but also ownership, which is sensitive to spatial location [Ratcliffe and Newport 2017]. An alternative is to not handle collisions for this type of movements. If users experience a high sense of presence (i.e. the sense of being in the VE), it was found that they can intuitively avoid collisions, especially when using a realistic avatar [Ogawa et al. 2020b]. For finer motion, it was found that handling collisions is preferred by users (see in Section 1.4.2.4).

Second, constraints separating DoF (for example to move precisely an object on one direction) can also create big mismatches between the user's position and the avatar's one. In such a case, it is possible to use explicit constraints. They can be explicitly defined by the users so they know what motion they can perform or not [Hayatpur et al. 2019]. It is also possible to use gestures to determine customised constraints [Gloumeau et al. 2021], which has the advantage of making users move their avatar and potentially appropriate it. To reduce DoF, the classical use of widgets (see an example on Figure 1.9) explicitly constrains the manipulation, which can be more predictable and impact less the sense of agency. Widgets can be seen as virtual objects that the user can use to indirectly manipulate objects. Common constraints on the manipulation still apply to the widgets though, for example the grabbing of the widget tool must seem realistic (see Section 1.4.2.4). While widgets are intuitive, they do not provide high-fidelity interaction using directly the avatar. New techniques of DoF separation adapted to the avatar could be invented.

Another way to handle constraints could be to dissociate the avatar, that provides a realistic representation of the user, from a second form of representation that is not affected by the constraints. It can be the tool used, a ghost [Yang and Kim 2002] or a skeleton hand [Argelaguet et al. 2016].

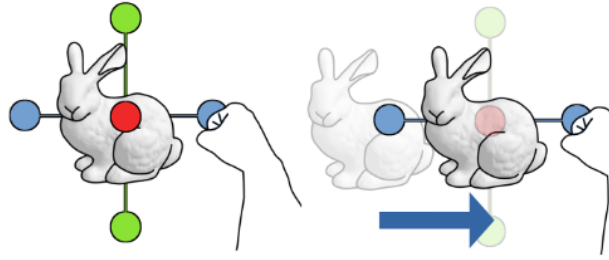


Figure 1.9 – Example of a widget to constrain manipulation. Image from [Mendes et al. 2016].

1.4.2.2 Remapped Motion: Modification of CD gain

Avatars provide a direct visual feedback of the user’s position and motion in the environment. If the CD gain differs from one, this relation between the user’s motion and the avatar’s one is altered and can impact the sense of embodiment. Typically, interaction methods employ either constant or adaptive gains.

Constant gains The higher or lower is the CD gain, the higher will be the mismatch between the avatar’s hand and the user’s real hand. Although visual feedback dominates proprioception [Burns et al. 2005], and people do not notice easily motion distortion (i.e. when their motion is amplified or decreased when achieving a task) [Debarba et al. 2018] and can even adapt their motion to this distortion [Bourdin et al. 2019], if the mismatch is too important it can frustrate the user and break the sense of embodiment. A study found that while the senses of agency and ownership are quite resistant to visual-proprioceptive mismatches (induced by a constant offset between the real and virtual hand), the sense of self-location is very sensible to them [Pritchard et al. 2016]. Moreover, Kokkinara et al. [2015] found that when users’ movements are amplified, this affects their perception of the VE and agency (contrary to the study by Pritchard et al. [2016]), but not ownership. When the user’s motion is distorted and it creates a mismatch that is noticeable, the user can therefore feel out of control and the sense of agency can be affected. To avoid this, it is better to do not apply gain, especially on fast and wide movements because it would quickly create a large mismatch between real and virtual hand. As discussed in Section 1.3.2, realistic hands make remapped motion less noticeable [Ogawa et al. 2020a]. Furthermore, instead of modifying the virtual body’s motion, the distortion can also be applied on the virtual world [Azmandian et al. 2016]. This is the same principle

as redirected walking, the world is translated when users move their head. This is only adapted to manipulation tasks necessitating head motions. A hybrid solution mixing world and body movements distortion can avoid the drawbacks of both techniques. Other tricks can be used especially after the distortion during offset correction, such as correcting the offset when the user closes the eyes [Zenner et al. 2021].

Adaptive gains The gain applied could also be adaptive, i.e. its value can vary depending on the conditions. For example, the gain can depend on the distance of the object to the user, closer manipulation necessitating a lower gain to be precise, and further manipulation a higher gain [Ouramdane et al. 2006]. It was found that the acceptance of distorted motion is increased when the distortion is gradually introduced [Porssut et al. 2019]. Altering the motion gain slowly in the context of physically tiring tasks still elicits a sense of ownership [Feuchtner and Müller 2018; Wentzel et al. 2020]. When distortion must be used in an application, it is better to adapt it depending on the situation. Different gains could also be applied depending on the direction of the movement, as users' notice more easily offsets on the horizontal axis than in other dimensions [Esmaeili et al. 2020].

An alternative to avoid the impact of distorted motion on embodiment could be to decouple the tool from the body. An isomorphic control would be kept for the avatar, while the manipulation would be anisomorphic [Gloumeau et al. 2021]. The gains would only be applied on the tool, thus not affecting the avatar itself, for example in out-of-reach interaction. **In this thesis, we propose another alternative, which is to use a dual body representation, made of an interactive representation showing distorted motion, and a co-located representation showing real motion. This alternative is presented in Chapter 4.**

1.4.2.3 Out-of-reach Manipulation

A special type of manipulation that can create a strong mismatch and potentially impact embodiment is out-of-reach manipulation. In the space in which we can reach objects, i.e. our peripersonal space, the challenge is mostly focused on the range of motion, the hand poses, the feedback of actions, or the display of input device. However, outside the peripersonal space, it is necessary to choose how to represent the action, and how it impacts the avatar. Common out-of-reach manipulation techniques are the Go-Go [Poupyrev et al. 1996] and the raycasting techniques [Bolt 1980].

The Go-Go technique applies a non-linear CD gain to the user’s input. The more users extend their arm, the further the virtual hand goes. If the limit of CD gain is too high, the mismatch can be important between the user’s real hand position and its virtual counterpart. This could potentially impact all the sense of embodiment components. Several choices of feedback can be considered in this problem [Feuchtner and Müller 2017], but all of them can highly impact the sense of embodiment. In the case of full-body avatars, the hand could be detached from the virtual body. However, it has been found that body discontinuity reduces body ownership but does not necessarily impact motor performance [Seinfeld and Müller 2020]. A hand attached to the arm by a rigid wire disturbs embodiment but not skin conductance in reaction to a threat [Tieri et al. 2015]. A potential solution could be to have an extensible arm, which can maintain a correct sense of embodiment, until reaching a certain length [Kilteni et al. 2012b]. Other feedback can be imagined, like a robotic extensible arm, a ghost clone of the hand going towards the object (as already used in training [Yang and Kim 2002]), or an outside assistance like a drone going to the object instead of the user’s body. It depends on the context of the application, if the realism must be maintained or not.

The Raycasting technique originally comes from the pointing technique [Bolt 1980] with an additional ray to provide visual feedback of selected objects [Mine 1995]. It has the advantage of being body-referenced but not part of the avatar. However, depending on the way it is represented, it may impact ownership by providing an unrealistic feedback. If we consider the basic raycasting in which the ray is linked to the hand, we can display the ray coming from a finger, probably the index because it is the finger associated to pointing. We could also display a laser pointer in the avatar’s hand instead, to maintain realism. The choice can also be impacted by the device input, if we use hand tracking we might prefer the first option, while the second could be better when a controller is used, or even a tracked stylus [Teather and Stuerzlinger 2011]. Other raycasting techniques exist, referenced to other parts of the body, for example to the head. In this case, a virtual headlamp could be used as a more coherent feedback.

The two techniques both have their pros and cons. The Go-Go technique uses direct manipulation, which is more intuitive and uses the avatar to appropriate it. The raycasting technique might be safer for self-location and agency, as it does not modify the CD gain and the virtual body does not have to be modified or reshaped to use this technique.

More variants of feedback for out-of-reach techniques and their impact on embodiment should be investigated. The ideal would be to invent a technique that is as intuitive as the Go-Go technique but does not have to modify the avatar.

1.4.2.4 Control of Dexterous Hand Interactions

Grabbing virtual objects is probably one of the hardest challenges in manipulation. Because of the lack of haptic feedback in VE, if a one-to-one mapping is applied to hand movements, visual artifacts can appear: unrealistic hand poses or fingers passing through objects. This can affect embodiment. However, it is known that humans are more sensible to visual interpenetration than proprioceptive offsets [Burns et al. 2005]. They tend to believe more what they see than what their proprioception tells them. Designers therefore often choose to handle collisions and to define hand poses on the virtual objects, so the user is not disturbed by interpenetrations. This solution is usually preferred by the users, even though it can decrease performance [Prachyabrued and Borst 2012b]. But, if users feel too constrained by the collisions, this may impact the sense of agency and self-location. This also applies for defined hand poses: if they are too different from users' real poses, this could affect embodiment. People usually tend to adapt to the visual feedback provided, and can be disturbed for example when the input action required is different from the feedback. This was noticed for example in the experiment by Lok et al. [2003] in which participants had to do a pinch movement but observed a grasping animation. Several participants started performing a grasp movement. Such adaptation needed might potentially influence the sense of embodiment.

The preferred feedback during the grasping of a ball has been studied, which confirms that handling collisions for fine manipulation is preferred [Canales et al. 2019]. Participants preferred visualising their hand outside the object, even though their real fingers were actually entering the sphere. This condition preserved the sense of ownership. Providing complete control of the virtual hand does not always seem to be the best choice.

Assistance in taking virtual objects is often used to make the manipulation more intuitive and realistic. This can be used without affecting agency and ownership [Porssut et al. 2019]. However, if too few hand poses are provided, users may feel limited in their actions, which could impact the sense of agency. If users can grab an object even with unrealistic hand poses, the application will lack realism. Since defining many hand poses in a VR application can be time-consuming, it would be interesting to study their influence on the sense of embodiment, especially agency.

1.4.2.5 One-to-One Mapping or Animation

With tracking solutions improving, it is tempting to track exactly users' motions and map them directly to the avatar. This is not always possible as most of the tracking systems are still cumbersome or expensive to deploy extensively. Moreover, when the tracking is imperfect, this can create breaks in embodiment as users can notice the discrepancies [Koiliias et al. 2019; Kokkinara et al. 2015]. There are therefore some papers comparing tracking solutions such as Inverse Kinematics (IK) to animations or hybrid solutions. For example, a locomotion technique that was recently studied in relation with the sense of embodiment is Walking-in-Place (WIP). A first preliminary study investigated two different feedbacks during WIP: an avatar stepping like the user, or an avatar walking [Park and Jang 2019]. Participants reported a preference for the natural walking animation, although it would sometimes display unintended steps. Another study compared a fixed body, a pre-recorded animation and an animation synchronised with users' leg movements using a deep-neural network [Lee et al. 2020]. It was found that the synchronised animation was better for ownership. A second experiment in the same study showed that this effect emerges whether users look directly at the legs or at the avatar's shadow. In line with these results, a study investigating prioritised factors to elicit a global sense of embodiment found that when people can progressively improve several factors, they prioritise control over appearance [Fribourg et al. 2020a]. The choice of controlling their avatar with IK instead of having an automatically launched animation was done before improving avatar appearance, and this was particularly the case for a soccer task where it was chosen before selecting a 1PP. While people like having full control over their avatar, a perfect one-to-one mapping is not always necessary. Movements can be distorted to have a visually realistic interaction while still feeling in control [Porssut et al. 2019]. Movement assistance is a good trade-off to ensure both sense of agency and reliability.

1.4.3 Impact of Feedback

The feedback provided to the user while performing an action can also impact embodiment. First the avatar itself is part of the feedback and can impact embodiment; for example if it is modified during manipulation. However, the type and characteristics of the feedback provided during an action can also affect embodiment.

1.4.3.1 Avatar Appearance During Interaction

The avatar is the main source of feedback during motion in the VE. To increase usability or performance, its appearance can be modified during manipulation (see Section 1.3.1.2). However, these changes must be done carefully. Even though avatar appearance is not the most important factor in the sense of embodiment [Fribourg et al. 2020a], several studies showed its importance in inducing a good sense of ownership [Waltemate et al. 2018]. Designers must be aware that modifying it can impact how much users feel like the avatar is part of their real body. For example, the avatar’s hands can be made transparent to avoid occlusions. But, if the hands are too transparent, this might impact the sense of ownership [Martini et al. 2015] and agency [Buchmann et al. 2005]. It is also possible to use skeleton hands [Argelaguet et al. 2016], which provide a good sense of agency but a lower sense of ownership than realistic hands. To ensure a good sense of ownership, it seems important to keep a realistic avatar.

When a tool is necessary for manipulation, or when a controller is used as input device, the feedback at the hand’s level can be either the hand (controlled by the input device, for example by mapping buttons to the movements of the hand) or the tool held in the hand. The feedback chosen and its coherency with the input device used might impact embodiment. While some studies start investigating this question [Alzayat et al. 2019], this topic needs further research.

1.4.3.2 Perspective

Perspective is the user’s point of view on the VE. Perspective is important to perform an action precisely, especially when the user can only rely on visual feedback. In applications using an avatar, various camera positions can be used, each of them providing a different amount of visual information. Perspective is generally described as a third-person perspective (the viewpoint is outside the user representation) or a first-person perspective (the user representation is co-located with the real body) (see Figure 1.10). A third-person perspective (3PP) is usually advised for navigation because it provides a better spatial awareness, but some recent work found that a first-person perspective (1PP) is actually preferred [Medeiros et al. 2018]. Similarly, Kokkinara et al. [2016] found that 1PP elicited higher senses of ownership and agency when seated users looked at their virtual avatar walking. For manipulation, a 1PP is usually preferred and more precise [Salamin et al. 2006; Gorisse et al. 2017] as the user can directly manipulate objects like they would in

real life. Moreover, a 3PP requires an additional cognitive load for considering both the transformation users want to apply to a virtual object and the offset between their vision and their avatar.

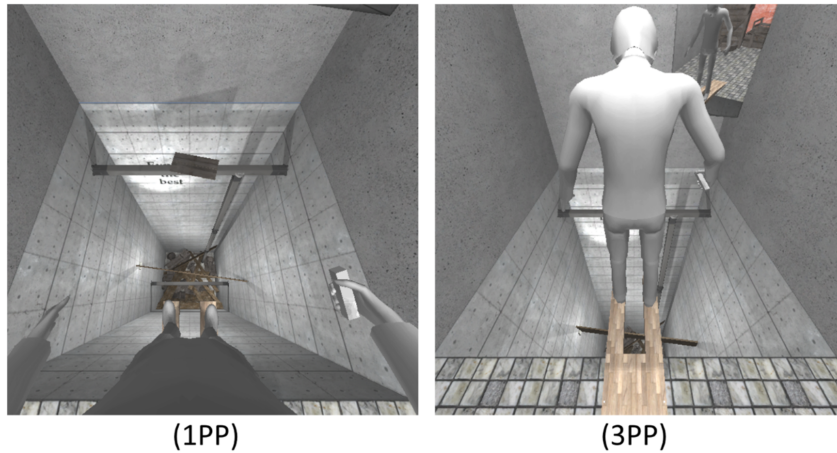


Figure 1.10 – First-person perspective vs. third-person perspective. Image from [Galvan Debarba et al. 2017].

In the literature on the role of perspective on the sense of embodiment, it was found that a 1PP is preferred to elicit embodiment. It was found that subjects experience a higher sense of ownership from a 1PP, even though it can be experienced from a 3PP to some extent with a synchronous motor feedback [Galvan Debarba et al. 2017; Gorisse et al. 2017]. The sense of agency seems less impacted by the perspective, and can be felt either from 1PP or 3PP as long as the movements are synchronised. Regarding the sense of self-location, studies have shown that a 3PP usually provokes a drop in the sense of self-location [Maselli and Slater 2014; Gorisse et al. 2017]. A potential solution, more complicated to implement, would be to have both perspectives [Salamin et al. 2008].

In conclusion, it is better to have a 1PP to provide both an efficient interaction and a high level of embodiment.

1.4.3.3 Haptic Feedback

Visual feedback is the main feedback provided in VR. However, in real life, people receive other types of feedback that help during manipulation. Additional feedback like haptic feedback [Hirota and Hirose 1995] can also be provided in VR and can impact manipulation performance [Swapp et al. 2006]. Haptic feedback can be provided through tactile feedback (touch, to feel the texture of the object for example) or force feedback

(e.g. users feel a resistance when they collide with an object) [Burdea and Brooks 1996]. There are nowadays output devices that are put directly on the body [Spanlang et al. 2010] that provide vibrotactile feedback and can make the user more aware of their virtual body. Synchronous visuotactile feedback provided by an experimenter was one of the first methods used to elicit embodiment towards a virtual body [Slater et al. 2008]. If users feel a touch and observe at the same time a stimulation on the virtual body that can cause this touch, the brain interprets that the virtual body must be their body. A study found that haptic feedback provided by wearable devices can increase the sense of embodiment [Fröhner et al. 2019], especially force feedback. A recent study also supports these results, as they found that interaction force feedback had a positive effect on the sense of agency, but no main effect on the sense of ownership [Akselrod et al. 2021]. With mid-air interfaces, audio and haptic feedback can be more efficient to increase the sense of agency than visual feedback [Cornelio Martinez et al. 2017]. In addition of the information it provides during manipulation, haptic feedback is therefore also a way of increasing the sense of embodiment and should be used when possible. It can also be beneficial during locomotion. For example, it was found that providing proprioceptive feedback using tendon vibration while looking at the avatar walking can enhance the sense of embodiment [Leonardis et al. 2014].

When it is not possible to provide haptic feedback, pseudo-haptic feedback can be used. This technique can create an illusion of weight by modulating the gain applied to users' motion [Jauregui et al. 2014]. However, this should be used with precaution when using avatars as it can create a mismatch between users and their avatar (see Section 1.4.2.2).

1.4.3.4 Auditory Feedback

Another type of feedback that can be provided to users is auditory feedback. Auditory feedback provides important information when manipulating objects in real life. Like haptic feedback, it can inform us of collisions, it can also help in perceiving textures [Kyung and Kwon 2006]. However, its relation with the sense of embodiment has been less studied than other types of feedback. The major study on auditory feedback and virtual embodiment is from Tajadura et al. [2017] who found that we can enhance embodiment of a child's virtual body when the avatar's voice and appearance are coherent. One study investigated the role of auditory cues in the RHI. Synchronous auditory feedback seems to strengthen the illusion [Radziun and Ehrsson 2018]. With a task of clapping hands in a non-immersive VE, no significant effect of the auditory feedback on virtual body owner-

ship was found, showing a potential low impact of this type of feedback in the ownership illusion [Lugrin et al. 2016]. Several studies exist on the link between body perception and sound [Azañón et al. 2016]. For example, when the sound heard when a small hammer hits a person’s hand is the sound of a hammer hitting a piece of marble, it can give the person the illusion that the hand is made of marble [Senna et al. 2014]. Because the sound informs the user of a contact with an object, it can also be used to create a long arm illusion [Tajadura-Jiménez et al. 2015b]. During locomotion, audio frequency can impact body weight perception [Tajadura-Jiménez et al. 2015a]. However, to our knowledge, no study has been done on the impact of auditory feedback during interaction on the sense of embodiment.

1.4.3.5 Make the Avatar Central

To have interaction techniques compatible with an avatar, the idea is to make the avatar central for the interaction. Techniques that are based on the body itself (using it as input or as spatial reference) are inherently more compatible with an avatar. Techniques that have been invented to use proprioception for example, use the body as a reference [Slater and Usoh 1994; Mine et al. 1997]. This has also the advantage of making users process information more rapidly, as information placed on or near the body improves information detection in some tasks [Seinfeld et al. 2020b].

There are therefore interrelations between the sense of embodiment and interaction techniques. From the knowledge on these interrelations, it is possible to adapt existing techniques to make them more compatible with avatars, and to invent new techniques that will be inherently compatible with avatars. **The state of the art shows more existing papers on manipulation techniques and virtual embodiment than for other types of interaction techniques. From the analysis of existing literature, we proposed several preliminary guidelines for manipulation techniques compatible with avatars that will be presented in Chapter 5.**

1.5 Conclusion of the State of the Art

VR immerses users in a whole new world. In this alternative world, avatars are useful to interact with the environment, i.e. to manipulate objects or navigate in this environment. To fully experience having a new body, it is better to feel like it is our real body. Sense of embodiment in VR is a recent and ongoing topic of research, inspired by real-

world illusions such as the RHI. It is still unclear how it is elicited and why its level differs between individuals. Moreover, while being able to act through a body is an efficient way to appropriate it, the impact of interaction on embodiment has been little studied. While some studies start showing interrelations between sense of embodiment and interaction in VR, especially for manipulation techniques, we lack knowledge on the impact of virtual representations on existing interaction techniques. We also do not fully understand yet how interaction design choices can affect the different components of embodiment. Interaction tasks in VR are various, from object manipulation to locomotion, as could be their interrelations with embodiment. There is therefore a need of better understanding these interrelations to design new techniques, more compatible with high-fidelity avatars. The goal is to have rich interaction and customised full-body avatars in future VR applications to fully experience all the advantages of VR.

As a first step, the next chapter will focus on the sense of embodiment and why it may be elicited differently between users.

UNDERSTANDING INDIVIDUAL DIFFERENCES IN THE SENSE OF EMBODIMENT

Abstract: This chapter reports an exploratory study aiming at identifying user internal factors (personality traits and body awareness) that might cause either a resistance or a predisposition to feel a sense of embodiment towards a virtual avatar. To this purpose, we conducted an experiment (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. The participants’ sense of embodiment was measured, as well as several personality traits (Big Five traits and locus of control) and body awareness, to evaluate the influence of participants’ personality on the acceptance of the virtual body.

2.1 Introduction

The sense of embodiment is the central aspect linking users to their avatar. In the related work, we presented many studies that investigated external factors influencing the sense of embodiment. These factors are linked to the avatar itself (e.g., appearance [Banakou et al. 2013; Peck et al. 2013], realism [Maselli and Slater 2013]) or to the apparatus (e.g., degree of control [Debarba et al. 2018], nature of the stimulation [Kokkinara and Slater 2014]). However, they are “external factors”, i.e., mostly linked to the avatar itself or to the experiment protocol, but not “internal factors”, i.e. linked to the user’s characteristics (e.g. personality or background experience). Indeed, while most studies are able to show general trends of the influence of such “external” factors, the inter-user variabil-

ity remains non-negligible. In practice, we can observe that some people easily believe in the illusion, while others are on the contrary totally refractory. This observation led us to investigate how individual differences could influence the sense of embodiment in VR. Such individual differences have been found for the sense of presence [Sacau et al. 2005; Murray et al. 2007], or for the RHI [Asai et al. 2011; Kállai et al. 2015]. Better understanding the emergence of different embodiment scores between individuals could be a key to also understand better how embodiment is elicited, and to better control participant samples in embodiment experiments. The aim of this chapter is to study such potential individual factors influencing the sense of embodiment, to better understand this phenomenon. We therefore conducted an exploratory experiment where we investigated the link between “internal” factors (personality traits and body awareness) and the sense of embodiment. This experiment 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 visuo-motor tasks (see Figure 2.1, left) and in the threat phase, a virtual character appeared in the environment and threatened the avatar’s hand with a knife (see Figure 2.1, right).

2.2 Experiment Design



Figure 2.1 – 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.

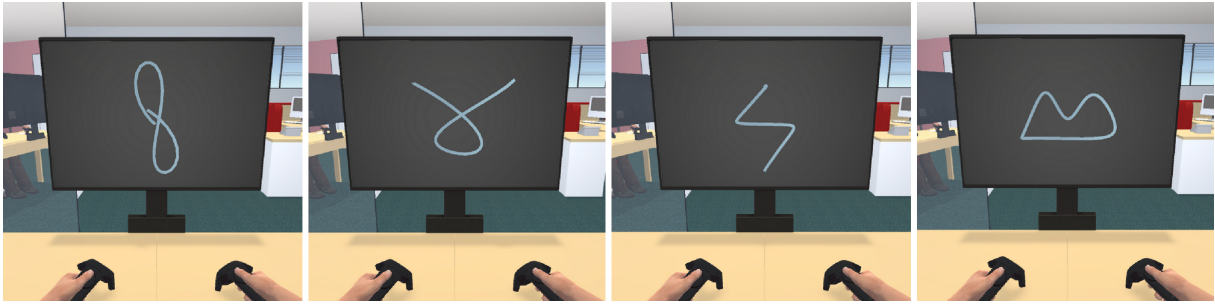


Figure 2.2 – Examples of four trajectories that participants were instructed to perform during the experiment with either their left or their right hand.

2.2.1 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 VR. 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.

2.2.2 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 adaptation 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 VE 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 held in their hands the real controllers that were also represented in the virtual world for coherence concern. A virtual screen was positioned in front of them, on the table, and a virtual mirror was located on their left (Figure 2.1). We chose to use a mirror as it is supposed to induce a greater sense of ownership [González-Franco et al. 2010; 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 2.2), 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 both 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 2.2.4.

2.2.3 Apparatus

The experiment was developed using Unity 2018.1.6f1. Participants saw the VE through an HTC Vive PRO HMD, while their hand movements were tracked using the Vive con-



Figure 2.3 – The two avatar models used in our experiments, which were matched to the gender of the participant.

trollers. 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 hands (controllers) movements. During the experiment, two avatar models were used to match the participant’s gender (see the male and female avatars in Figure 2.3). Because appearance is a major contributor to the sense of embodiment, using personalised avatars might lead to high embodiment ratings for most participants [Waltemate 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 2.1, right).

2.2.4 Collected Data

2.2.4.1 Embodiment and Presence Questionnaires

To measure embodiment, participants were asked to fill in the subjective questionnaire proposed by Gonzalez-Franco and Peck [2018]. It is composed of questions divided in several categories: body ownership, agency, tactile sensations (not used in our experiment), location, external appearance and response to external stimuli (referred to as *threat per-*

ception in this chapter). Participants therefore answered 19 questions on a 7-point Likert scale.

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, despite the already important number of questionnaires in our study. 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.

2.2.4.2 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 et al. 2007], suggesting that they consider the virtual body to be their own.

2.2.4.3 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. It is also important to mention that the experiment was conducted on a French campus, and that we therefore used the French validated translation of these international questionnaires in our experiment. All the Likert scales used are the ones pro-

posed in each validated questionnaire, going from the lower bound (strong disagreement) to the upper bound (strong agreement).

1) 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 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; B elisle 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 with 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: Are some of the users’ Big Five traits 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?

2) 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 et al. [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/she can change events with his/her 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?

3) 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 et al. 2014], another study showed that it could be disturbed by the body ownership illusion [Tsakiris 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?

2.3 Results

In order to analyse the link between internal factors and the sense of embodiment, Section 2.3.1 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 2.3.3 analyses the behavioural responses and Section 2.3.4 the presence results.

2.3.1 Embodiment Questionnaire (Version 1) Analysis

The analysis in this section was performed using the embodiment questionnaire filled in by the participants, i.e. the version from 2018 [González-Franco and Peck 2018]. An additional analysis inspired by the second version of the questionnaire will be presented in the following section.

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 2.1, separated by men and women answers when relevant.

In order to prevent such differences from adding 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 explore 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 on 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

Table 2.1 – 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]	

Table 2.2 – Contributions (i.e. weights) of the different questions to the men ownership (O_M), women ownership (O_W), agency (A), external appearance (EA), and threat perception (T) components.

	$O_{PC1,M}$	$O_{PC2,M}$		A_{PC1}
O1	0.740		A1	0.722
O2	-0.475	0.623	A2	0.827
O3	0.102	0.966	A3	-0.443
O4	0.722		A4	-0.713
O5	-0.756			
	$O_{PC1,F}$	$O_{PC2,F}$		EA_{PC1}
O1	0.471	0.272	EA1	0.716
O2	-0.846		EA2	0.719
O3	0.829		EA3	0.727
O4		0.864	EA4	0.705
O5		-0.822		
				T_{PC1}
			T1	0.919
			T2	0.913
			T3	0.915
			T4	0.917

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 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 Gonzalez-Franco and Peck’s questionnaire [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 2.4, and exact values in Table 2.2).

Pearson correlations were then computed (see summary in Table 2.5) 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.

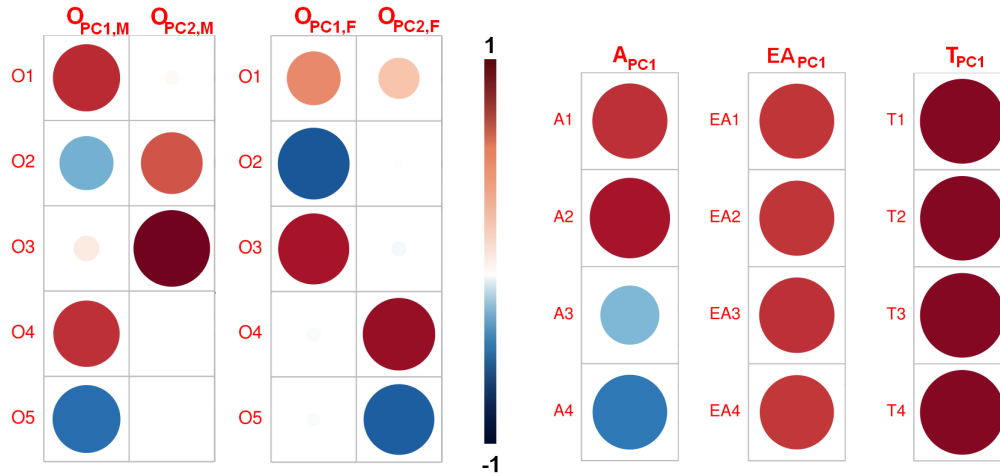


Figure 2.4 – Contributions (i.e. weights) of the embodiment questions to the different components ($O_{PC1,M}$ and $O_{PC2,M}$ (for men), $O_{PC1,F}$ and $O_{PC2,F}$ (for women), A_{PC1} , EA_{PC1} , T_{PC1}).

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 2.3.

2.3.1.1 Body Ownership

As answers to body ownership questions were significantly different for men and women, we performed 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 ($r = 0.248$, $p = 0.047$). As we did not find correlations between $O_{PC2,M}$ and any of the variables, we do not consider it further.

Table 2.3 – Multiple linear regression models for embodiment
 (* : $p < 0.05$; ** : $p < 0.01$; *** : $p < 0.001$)

$\mathbf{O}_{PC1,M}$			\mathbf{A}_{PC1}		
Variables	β	$Pr(> t)$	Variables	β	$Pr(> t)$
Internal	0.059	0.003 **	Agreeableness	0.005	0.122
Chance	0.054	0.004 **	Internal	0.026	0.003 **
Body Awareness	-0.013	0.038 *	Body Awareness	-0.006	0.077

$\mathbf{O}_{PC1,F}$			\mathbf{EA}_{PC1} for men		
Variables	β	$Pr(> t)$	Variables	β	$Pr(> t)$
Openness	-0.010	0.021 *	Neuroticism	0.285	0.036 *
Conscientiousness	-0.008	0.068	Internal	1.865	0.001 ***
Internal	0.038	0.006 **	Chance	0.843	0.102
Powerful	-0.026	0.055			
Chance	0.038	0.010 **			
Body Awareness	-0.010	0.044 *			

$\mathbf{O}_{PC2,F}$			\mathbf{EA}_{PC1} for women		
Variables	β	$Pr(> t)$	Variables	β	$Pr(> t)$
Extraversion	0.006	0.112	Chance	1.230	0.017 *
Powerful	0.036	0.024 *			
Chance	0.027	0.099			
Body Awareness	-0.008	0.174			

\mathbf{T}_{PC1}		
Variables	β	$Pr(> t)$
Agreeableness	0.465	0.029 *
Neuroticism	0.457	0.002 **

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 O5.

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 $R^2 = 0.239, p = 0.002$).

2.3.1.2 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 ($r = 0.184, p = 0.04$).

2.3.1.3 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 $R^2 = 0.081$, $p = 0.017$).

2.3.1.4 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 $R^2 = 0.088$, $p = 0.001$).

2.3.2 Additional Analysis: Embodiment Questionnaire (Version 2)

We performed an additional analysis with the updated version of the embodiment questionnaire [Peck and Gonzalez-Franco 2021]. This version has 16 questions (instead of 25 in the first version) that are classified into four components obtained from a PCA. It was published after we performed the first analysis, but we wanted to support a posteriori the validity of our results. Because we did not include several questions in our study (question R2 about proprioceptive drift because the avatar was co-located, question R7 because we did not need a customised question, and questions R14 to R16 because we had no tactile stimulation), we could not perform the analysis recommended in the paper. An analysis with a PCA, similar to the one performed to obtain the new version of the embodiment questionnaire, was therefore performed instead. The goal was to see whether the components obtained were similar to the ones found in the second version of the questionnaire, and whether the results for our study were still similar.

In this study, we used 19 out of the 24 questions from the first version of the questionnaire. First, the Pearson correlations between the different questions scores were computed. If the questions were correlated ($r > 0.3$) with less than three other questions, or too highly correlated with other questions ($r > 0.9$), they were removed. At this step, questions A2, A4, L1 and EA3 were removed because they were correlated with less than three other questions. Then, the individual Kaiser-Meyer-Olkin (KMO) value for each remaining question was computed. Question O5 had the lowest KMO value (0.56) and was correlated ($r > 0.3$) with only three other questions, therefore we decided to remove it. At the end, only 14 questions remained.

On these 14 questions, a Polychoric PCA was conducted. Using the empirical Kaiser criterion (the eigen value must be greater or equal to one), three principal components were kept. The fourth component had an eigen value equal to 0.98, which is close to 1. To explain more than 60% of the variance, we decided to keep four components. We then performed an oblimin rotation and kept questions having a loading greater than |0.4|. As performed by Peck and Gonzalez-Franco [2021], we computed the score for each component with equal weight for each question, which gave the following formula:

- TC1: T1 + T2 + T3 + T4 (questions about perception of threat)
- TC2: O1 - O2 + O4 + EA4 (questions about ownership and appearance)
- TC3: O3 + A3 + L2 + EA1 + EA2 (questions mostly about feeling out of the body or losing control)
- TC4: -O2 + A1 (one question about ownership and one about agency)

These components explain 65.4% of the variance. We then computed the correlations between these components and the different psychological variables (Big Five traits, LoC and body awareness). We found a positive correlation between TC1 and Neuroticism ($r = 0.258$, $p < 0.01$) which is in line with results from the first version of the questionnaire. We also found positive correlations between TC2 (asking globally about ownership) and both Internal ($r = 0.239$, $p < 0.01$) and Chance LoC ($r = 0.252$, $p < 0.01$). This is similar to correlations already found in the previous analysis, where external appearance was correlated to both Internal and Chance LoC. TC3 was positively correlated with both Neuroticism ($r = 0.181$, $p < 0.05$) and Chance ($r = 0.186$, $p < 0.05$). It is difficult to compare this result to the previous ones, as this component mixes several categories of questions. Finally, TC4 (asking about being in control and the avatar not being someone else) was positively correlated with Internal LoC ($r = 0.287$, $p < 0.01$), which is also in line with previous results.

2.3.3 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 ($\beta = -0.062, p = 0.140$).

2.3.4 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 ($r = 0.203, p = 0.024$) (see Table 2.4).

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

Table 2.4 – Multiple linear regression models for presence
 (* : $p < 0.05$; ** : $p < 0.01$)

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

2.3.5 Additional 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 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 ($O_{PC1,M}$: $r = 0.355$, $p = 0.004$; $r = 0.289$, $p = 0.028$).

2.4 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 2.5 – 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							

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

2.4.1 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.

2.4.1.1 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 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.

2.4.1.2 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.

2.4.1.3 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.

2.4.1.4 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 VE

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 did observe 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.

2.4.2 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].

2.5 Conclusion

In this chapter, we presented an exploratory study on the impact of personality traits and body awareness on the sense of embodiment. The major finding of the experiment is that the locus of control is linked to several components of embodiment: the sense of agency is positively correlated with an internal locus of control and the sense of body ownership is positively correlated with an external locus of control. Interestingly, both components are not influenced by the same traits, which confirms that they can appear independently. Taken together our results suggest that the locus of control could be a good predictor of the sense of embodiment when the user embodies an avatar with a similar physical appearance. Given the amount of personality and cognitive models and

questionnaires in the literature, it was not possible to be exhaustive, and we decided to focus on some of the most common models. As future work, other personality traits could be explored. While this experiment included a visuomotor task, we did not study the impact of this task on embodiment. Nevertheless, interacting with the VE requires using the avatar and can therefore impact the sense of embodiment. In the following chapters, we will explore embodiment during locomotion and manipulation tasks. The next chapter will focus on the influence of locomotion technique on embodiment, as it has not been studied yet in the community.

STUDYING THE INTERRELATIONS BETWEEN LOCOMOTION TECHNIQUES AND EMBODIMENT

Abstract: This chapter explores the potential interrelations between locomotion and embodiment by focusing on the two following questions: Does the locomotion technique have an impact on the user’s sense of embodiment? Does embodying an avatar have an impact on the user’s preference and performance depending on the locomotion technique? To address these questions, we conducted a user study ($N = 60$) exploring the relationship between the locomotion technique and the user’s sense of embodiment over a virtual avatar seen from a first-person perspective. Three widely used locomotion techniques were evaluated: real walking, walking-in-place and virtual steering. All participants performed four different tasks involving a different awareness of their virtual avatar. Participants also performed the same tasks without being embodied in an avatar.

3.1 Introduction

Locomotion is an essential task in VEs, as it lets users move from one point to another, to explore the VE or to move towards an object. While there were already several studies investigating the link between manipulation techniques and embodiment [Lin et al. 2019], there was no study investigating the potential interrelations between locomotion techniques and virtual embodiment. Yet, locomotion techniques were found to influence the sense of presence, and the level of motion involvement could influence the way users perceive their virtual body. This chapter therefore investigates how locomotion techniques can impact the sense of embodiment, and how embodying an avatar can influence the way users navigate in the VE (in terms of performance and preference). To explore these effects, we conducted a mixed-design experiment in VR. We used three widely used locomotion



Figure 3.1 – Illustration of the four tasks performed by the participants in our user study, all in the full-body avatar condition. The same tasks were also performed without an avatar. From left to right: Training task, Corridor task, Path-following task and Columns task.

techniques as a between-subject factor: real walking, walking-in-place and head steering. We chose these techniques because they are all continuous locomotion techniques, with different levels of physical engagement and interaction fidelity. Participants performed four tasks in the VE, with two conditions on their virtual appearance (within-subject factor): full-body animated avatar or only 3D models of controllers.

3.2 Experiment

3.2.1 Participants

Sixty-five participants volunteered to take part in our experiment. The majority of them were students and staff from our research center. Five participants were removed from the study: two because of problems in data recording, two because of tracking issues and one because of motion sickness during the first block. In the end, sixty participants (age min=20, max=56, avg=28.9±8.4, 25 women and 35 men) took part in our study. Participants did not receive any compensation. They were all naive as to the purpose of the experiment, and gave written and informed consent. The study conformed to the declaration of Helsinki. Twenty-five participants reported having no or little previous experience in VR (score 1 or 2 out of 7), twenty-four to have some previous experience in VR (score between 3 and 5) and eleven to be experts (score 6 or 7 out of 7).

3.2.2 Apparatus

The experiment was developed using Unity (version 2019.1.0f2). Users were tracked using an HTC Vive PRO HMD (equipped with the HTC wireless adapter so that partic-

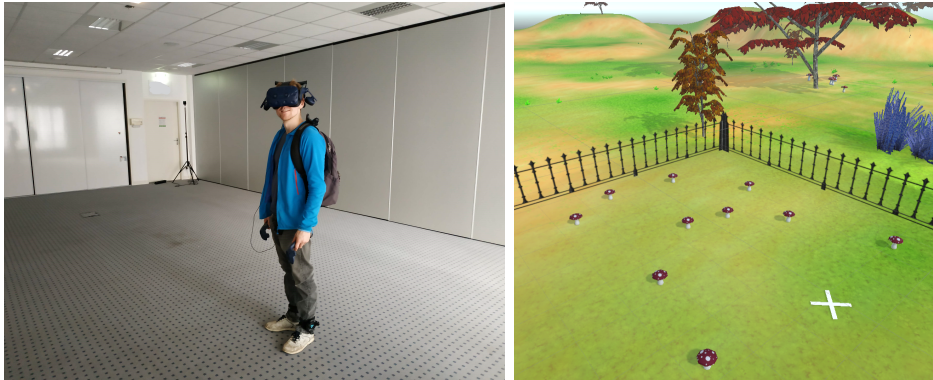


Figure 3.2 – Left: Setup in the physical environment. The HTC Vive with a wireless adapter was used to enable participants to physically walk in an $8m \times 8m$ area. The tracking of the user’s motions was enabled by the two hand controllers and two HTC Vive Trackers attached to their ankles. Two additional HTC Vive trackers were also positioned on a backpack to track participants’ shoulders. Tracking was done using four HTC Vive lighthouses. Right: Overview of the virtual environment: the navigation area was constrained by the virtual fences which matched the limits of the physical space.

participants were not hindered by the cable when navigating), two HTC Vive controllers, two HTC Vive trackers positioned on the ankles to track the feet, and two HTC Vive trackers positioned on a backpack to track the shoulders. We used four HTC Vive lighthouses to track an $8m \times 8m$ area. The VE consisted of a flat grassy ground surrounded by fences, matching the dimensions of the physical space, with trees and hills in the background (see Figure 3.2).

The positions of the headset, controllers and trackers on the ankles were used to animate the avatar, using inverse kinematics (FinalIK plugin). Participants were represented by gender-matched avatars (visible in Figure 3.1). During calibration, participants were asked to keep their feet and legs straight to adjust the avatar’s feet. They also had to stand straight to adjust the avatar’s global scale based on their height.

3.2.3 Locomotion Techniques

To better understand the influence of the presence of an avatar depending on the locomotion technique, we selected different locomotion techniques based on Boletsis’s taxonomy [Boletsis 2017]: room-scale-based, motion-based, controller-based and teleportation-based. In particular, we were interested in techniques that are commonly used in VR, and that involved a similar motion in the VE but different levels of physical movement. There-

fore, we chose the following techniques: Real Walking (RW; room-scale-based), Walking-In-Place (WIP; motion-based) and Steering (S; controller-based). Despite its inclusion in Boletsis’s taxonomy, we did not include teleportation in our study as it creates a discontinuous movement unlike the three other selected techniques. The different techniques are detailed below:

- **Real Walking (RW):** Participants could physically walk in an $8m \times 8m$ area. A one-to-one control mapping was kept between the physical and the virtual motions.
- **Walking-In-Place (WIP):** we implemented a WIP algorithm which detects walking patterns based on the position of the ankles [Kim et al. 2012; Bruno et al. 2013], which were tracked using Vive trackers. Locomotion was initiated whenever a first step was detected, i.e., when the two ankles’ position had consecutively passed above a given threshold (initial tracker position + $5cm$). It was stopped whenever a step had not been detected in the last $0.8s$. Because participants tend to take lower steps over time, the threshold was decreased to a value equal to the initial tracker position + $2cm$ after they started stepping. The thresholds were determined empirically through iterative design and several user tests. The direction was determined by the participant’s head orientation.
- **Steering (S):** in this technique, participants navigated in the VE using a constant navigation speed while keeping the Vive controller button held down, which is a common approach in both VR and video games. We chose a head-steering implementation (i.e., navigation direction determined by the participant’s head orientation), as it is commonly used, easy to get familiar with, and because the tasks in our experiment did not require looking in another direction than the one in which people were headed.

While previous work identified that people usually walk in real situations at a comfort speed of approximately $1.3m/s$ [Bohannon 1997], several studies demonstrated that participants tend to walk slower in an immersive VE [Mohler et al. 2007; Agethen et al. 2018; Berton et al. 2019], especially when wearing an HMD. We therefore set the navigation speed of both the Steering and Walking-In-Place techniques to $1.0m/s$, which should approximately match the speed observed while walking with an HMD [Agethen et al. 2018; Berton et al. 2019].

At this point, it also seems important to point out that for all three techniques in our experiment, the avatar’s movements were always driven by the participants’ actual

movements when they were embodied in a virtual avatar. This means that a) for the real walking technique, the avatar walked as the participant physically walked; b) for the walking-in-place technique, the avatar performed steps on the spot like the participant, while being translated forward in the direction in which participants were looking; c) for the virtual steering, since participants did not move forward in the real world, the avatar stood like the participant, moved its feet like the participant when they turned on the spot, or “slid” along the ground in the direction participants were looking towards.

3.2.4 Experimental Tasks

The experiment was divided into four tasks (see Figure 3.1), which were designed to ensure that participants were aware of their virtual body, i.e. that parts of the avatar were directly visible from the participant’s perspective. The main design principle for defining the tasks was to ensure that participants were able to see different parts of their virtual body during the experiment in a consistent way.

- **Training task:** The first task was a training task, which goal was to get participants used to the VE and the locomotion technique. More precisely, participants were instructed to navigate in the VE, in order to pick mushrooms on the ground by touching them with either hand. This task lasted one minute.
- **Corridor task:** The aim of this task was to enable participants to see their entire avatar moving, while navigating in a VE. They were therefore instructed to walk back and forth in a corridor with mirrors at both ends. A line in front of the mirror indicated where subjects were to turn around so as to not go through the mirror. This task lasted two minutes.
- **Path-following task:** The aim of this task was to force participants to look at their avatar, in particular at their feet, while navigating. They were therefore instructed to follow a target moving on an eight-shaped trajectory, both displayed at the ground level. The target was always 50cm ahead of them so that participants had to tilt their head, thus ensuring that the avatar’s legs were inside their field of view. This task lasted two minutes.
- **Columns task:** The aim of this task was to study people’s behaviour while navigating around virtual obstacles. They were instructed to navigate in a VE filled with 2-metre high columns and to pick mushrooms as in the training task. In this task, people could therefore mostly see their hands and arms. The mushrooms were

always placed at the same positions. They were displayed in groups of ten, with new mushrooms appearing once all those of a series were picked. The distance between columns was 1.45 times the shoulder width of the scaled avatar, to ensure that any participant could move through without necessarily turning their shoulders (which requires an aperture-to-shoulder ratio lower than 1.4 [Warren and Whang 1987; Mestre et al. 2016]). This task lasted two minutes.

The tasks were always presented in the same order: training, corridor, path-following and columns. As we were interested in evaluating the overall users' subjective experience, we considered that keeping the same order would reduce the variability in their subjective assessment. Furthermore, we did not compare the tasks with one another.

3.2.5 Experimental Protocol and Design

First, participants signed the consent form. Then they were equipped with the HMD, the controllers and the trackers.

We had two independent variables: Technique and Appearance. For the Technique, we used a between-subjects design, so each participant used only one of the three locomotion techniques presented in Section 3.2.3. There were twenty participants per group. For the Appearance condition, a within-subject design was chosen. Two levels were used: Full-Body Avatar (FBA) and No Avatar (NA). In the FBA condition, participants were represented by a full-body gender-matched avatar holding a 3D model of an HTC Vive controller in each hand, while in the NA condition, only the 3D models of the Vive controllers were displayed.

Therefore, the experiment was divided into two blocks (FBA and NA). In total, participants performed 2 x 4 tasks. To minimize potential ordering effects, the blocks were counterbalanced and there was a 5-minute break between them. Participants therefore either performed all the four tasks (in the order presented above) in the FBA condition, then all four tasks in the NA condition, or the opposite (see Table 3.1). The whole session lasted about 40 minutes, including the participant's welcome, performing the experiment, and answering questionnaires.

As dependent variables, we used both objective (performance) and subjective (user preference, embodiment) criteria.

3.2.5.1 Objective Data

Objective data were measured in only two tasks (path-following and columns tasks). No objective data were recorded during the training task as the aim of the task was only to make users familiar with the given locomotion technique. Similarly, there was no relevant performance criterion in the corridor task.

- **Path-following task:** The mean distance between the path to follow and the user’s position was computed as an objective measure of performance.
- **Columns task:** We measured both the number of mushrooms picked during the columns task, and the number of collisions with the columns, as an objective measure of performance. Because the number of collisions can also depend on the distance covered by participants, we normalized the number of collisions by the distance covered (in metres). We counted collisions between the participants’ shoulders (tracked by the additional Vive trackers) and columns, hereafter referred as shoulder collisions.

3.2.5.2 Subjective Data

Subjective questionnaires were also used to obtain user perception of the experience.

Embodiment questionnaire: We used the ownership, agency and self-location questions from the embodiment questionnaire proposed by Gonzalez-Franco and Peck [2018] (see Table 4.4). These questions were evaluated on a 7-point Likert scale from 1 (Strongly disagree) to 7 (Strongly agree). The questionnaire was administered only after the FBA block.

Representation questionnaire: After each block, participants were asked questions related to the virtual representation (R questions in Table 3.3). These questions were about both the virtual representation seen indirectly in the mirror and in other tasks from the first-person perspective. The goals of these questions were mainly to detect whether people were disturbed by their representation ($R_{MirrorLogical}$ and $R_{OtherLogical}$) and whether they appreciated it ($R_{MirrorPleasing}$ and $R_{OtherPleasing}$). Each item was measured on a 7-point semantic differential scale. Participants answered these questions once after each block.

Table 3.1 – The two possible orderings of the experiment based on the avatar factor. While the representation questionnaire was administered after each block, the embodiment questionnaire was only administered after the FBA condition.

1)	SSQ	Full-Body Avatar	Rep. + Embodiment	No Avatar	SSQ	Rep.	Comparison
2)	SSQ	No Avatar	Rep.	Full-Body Avatar	SSQ	Rep. + Embodiment	Comparison

Comparison questionnaire: Participants were also asked to answer several additional questions after the last block, related to whether they preferred the presence of an avatar or not (see Table 3.4). Questions $C_{preferBody}$, $C_{pathEasier}$ and $C_{columnsEasier}$ were rated on a 7-point semantic differential scale while question $C_{behaviourDifferent}$ was rated on a 7-point Likert scale. Participants could also associate an adjective with each Appearance condition, explaining why they preferred to have an avatar or not, as well as make free comments about the experiment.

SSQ: Additionally, the Simulator Sickness Questionnaire (SSQ) [Kennedy et al. 1993] was given to participants before and after the experiment, and we computed the difference between pre-experiment and post-experiment scores to verify that there were no differences in terms of sickness between the different conditions.

3.2.6 Hypotheses

Previous studies have shown the impact of physical implication on the sense of embodiment [Synofzik et al. 2008]. Moving in the VE seems to let the brain compare the movement intention with the feedback of the action, which is one of the ways to increase the sense of agency [Synofzik et al. 2013] if there is a match. This sense of agency can strengthen the sense of ownership [Kalckert and Ehrsson 2012]. Thus, we expected that the higher the match between proprioception and sensory feedback, the higher the felt embodiment would be, leading to the following hypothesis:

- H1** The sense of embodiment is influenced by the locomotion technique. In particular, we expected the sense of embodiment to be higher for techniques with a higher interaction fidelity (i.e., $RW > WIP > S$).

In addition, because an avatar provides a better spatial awareness [Draper et al. 1996], we expected that participants would avoid the columns more in the columns task with the FBA condition. Participants could also see the columns as a threat for their avatar. Thus our second main hypothesis was:

H2 The presence of an avatar leads to less collisions with the virtual environment.

Furthermore, we also included secondary hypotheses, related to the other collected variables:

H3 People find having a full-body avatar while navigating in a VE more pleasing and logical (R questions).

H4 People think that their representation is more disturbing when using WIP and S than RW (R questions).

3.3 Analysis

Mixed two-way ANOVA analyses were used taking into account both the Technique (between-subjects) and the Appearance (within-subjects) factors. We tested the normality assumption using the Shapiro-Wilk normality test. When the data were not normal, we applied an Aligned Rank Transformation (ART) on the data before performing the ANOVA analysis. Tukey HSD post-hoc tests ($\alpha = .05$) were conducted to check significance for pairwise comparisons. Kruskal-Wallis tests were however conducted when analysing results depending only on the Technique (between-subjects), as the Shapiro-Wilk tests significantly rejected the null hypothesis according to which the data were normally distributed. Dunn’s post-hoc tests were conducted to perform pairwise comparisons.

3.3.1 Effect of the Locomotion Technique on Embodiment

First of all, we used a Mann-Whitney’s test to identify potential ordering effects between the FBA and NA conditions. As we did not find any significant effect, order will not be considered in the remainder of the analysis.

We performed Kruskal-Wallis tests to explore differences in embodiment ratings between the different techniques, using the questions about the senses of ownership, agency and self-location. We only found a significant effect of the Technique on the question $SL_{located}$ about self-location ($\chi^2 = 9.623, p < 0.01$). Dunn’s test revealed that the RW

Table 3.2 – Summary for body ownership (O), agency (A) and self-location (SL) questionnaires. This table reports the median and interquartile range for each question. When significant differences (Kruskal-Wallis test) were found between techniques (NW, WIP, S), the descriptive statistics for each technique are provided.

ID	Questions	Median[Q1;Q3]		
		NW	WIP	S
<i>O_{ownBody}</i>	I felt as if the virtual body was my own body	5[3;6]		
<i>O_{someoneElse}</i>	I felt as if the virtual body I saw was someone else	4[2;5]		
<i>O_{moreOneBody}</i>	It seemed as if I might have more than one body	2[1;3]		
<i>O_{ownBodyMirror}</i>	I felt as if the virtual body I saw when looking in the mirror was my own body	4[2.75;5.25]		
<i>O_{someoneElseMirror}</i>	I felt as if the virtual body I saw when looking at myself in the mirror was another person	3[2;5]		
<i>A_{control}</i>	It felt like I could control the virtual body as if it was my own body	5[5;6]		
<i>A_{caused}</i>	The movements of the virtual body were caused by my movements	6[5;7]		
<i>A_{influencing}</i>	I felt as if the movements of the virtual body were influencing my own movements	3[2;5]		
<i>A_{movingItself}</i>	I felt as if the virtual body was moving by itself	2[1;3]		
<i>SL_{located}</i>	I felt as if my body was located where I saw the virtual body	6[6; 7] ¹	5[4; 6] ²	5[4; 6] ²
<i>SL_{outBody}</i>	I felt out of my body	2[1;4]		

Techniques sharing a superscript were not significantly different (Tukey HSD $\alpha = .05$)

Table 3.3 – Summary for subjective questions on the virtual representation (R). This table reports the median and interquartile range for each question. When main effects of appearance factor or interaction effects were found, the descriptive statistics for each appearance are provided.

ID	Questions	Median[Q1;Q3]	
		FBA	NA
$R_{MirrorLogical}$	When facing the mirror, my virtual representation when navigating in the VE was confusing(1)/logical(7)	5[3; 6]	4[3; 6]
$R_{OtherLogical}$	In other tasks, my virtual representation when navigating in the VE was confusing(1)/logical(7)	6[4;6.25]	
$R_{MirrorPleasing}$	When facing the mirror, my virtual representation when navigating in the VE was disturbing(1)/pleasing(7)	4[3;5]	
$R_{OtherPleasing}$	In other tasks, my virtual representation when navigating in the VE was disturbing(1)/pleasing(7)	5[4; 6]	4[4; 5.25]

* indicates that an interaction effect was found

Table 3.4 – Summary for comparison questionnaire. This table reports the median and interquartile range for each question. There was no significant effect (Kruskal-Wallis test) of the Technique factor.

ID	Questions	Median[Q1;Q3]		
		NW	WIP	S
$C_{preferBody}$	I preferred not having a body (1) vs. having a body (7)	5[3;6.25]		
$C_{pathEasier}$	I felt that performing the path-following task was easier without an avatar (1) vs. with an avatar (7)	4[3;6]		
$C_{columnsEasier}$	I felt that performing the columns task was easier without an avatar (1) vs. with an avatar (7)	4[4;5]		
$C_{behaviourDifferent}$	I have the impression that my behaviour was different with an avatar vs. without an avatar	5[4;6]		

condition obtained significantly higher scores than WIP and S conditions (see values in Table 4.4). We did not find any significant difference between any of the three techniques for all the other questions. These results therefore do not support **H1**. Medians and quartiles for each question are available in Table 4.4. Although not significantly different, the scores for the questions $O_{someoneElse}$ and $O_{someoneElseMirror}$ were higher for the RW condition. We also computed the overall ownership, agency and self-location ratings using the recommendations from Gonzalez Franco and Peck [2018], and did not find any significant difference. Overall, the agency ratings ($M = 5.00$, $SD = 0.81$) as well as self-location ratings ($M = 5.43$, $SD = 1.09$) were high. For ownership, the scores were slightly lower ($M = 4.60$,

$SD=1.21$).

3.3.2 Users' Performance and Collision Avoidance

We performed a mixed two-way ANOVA to study the potential differences between the different techniques (between-subjects factor) and the avatar conditions (within-subjects factor) on the objective measures of the path-following (mean distance to trajectory) and columns task (shoulder collisions, number of collected mushrooms). We did not find any main effect of the Appearance or interaction effects on these objective measures (see Table 3.5). In particular, this result does not support **H2** (no influence on the number of collisions). These results were also confirmed by participants' answers to the subjective questions about the ease of tasks (questions $C_{pathEasier}$ and $C_{columnsEasier}$ in Table 3.4, which results are detailed in Section 3.3.3.2). Participants did not find the task easier in one or the other Appearance condition, which is coherent with the objective data.

Table 3.5 – Performance results: mean distance to trajectory (in cm), ratio of shoulder collisions, and number of picked mushrooms.

	FBA	NA
Mean distance	$M = 8.14, SD = 2.96$	$M = 8.50, SD = 2.91$
Ratio shoulder collisions	$M = 0.35, SD = 0.41$	$M = 0.37, SD = 0.38$
Nb mushrooms	$M = 22.7, SD = 7.13$	$M = 23.45, SD = 6.41$

3.3.3 Users' Preferences

We also performed a mixed two-way ANOVA to explore the differences in the subjective answers between the different conditions (Technique and Appearance). Some questions were meant to indirectly compare appearance between the two blocks, while others were meant to directly ask participants which condition they preferred at the end of the experiment.

3.3.3.1 Representation questionnaire

For the questions about the virtual representation, we found a main effect of Appearance for the question $R_{MirrorLogical}$ ($F_{1,57} = 4.48, p < 0.05$). Post-hoc tests showed that participants felt that being embodied in an avatar was more logical ($Mdn = 5, IQR = 3 - 6$) than without ($Mdn = 4, IQR = 3 - 6$). We also found an effect of Appearance for the question

$R_{OtherPleasing}$ ($F_{1,57} = 9.341, p < 0.01$). Only the results of $R_{MirrorLogical}$ and $R_{OtherPleasing}$ support **H3**.

Also, we observed that participants provided lower ratings for the $R_{MirrorLogical}$ and $R_{MirrorPleasing}$ questions compared to $R_{OtherLogical}$ and $R_{OtherPleasing}$ respectively. Being in front of the mirror seemed to have a negative impact on the participants' answers.

No effect of the locomotion Technique was found on questions about representation, which does not support **H4**.

3.3.3.2 Comparison questionnaire

Regarding the questions directly asking participants to compare conditions, the results show a slight preference for the condition with an avatar, with all medians ≥ 4 for $C_{preferBody}$. Yet, we observed a polarization for S (see Figure 3.3), some participants not at all preferring having a virtual body (≤ 2), and others showing a high preference ($=7$). These results were not visible for the WIP and RW conditions in which participants provided more consistent answers with a slight preference over the avatar. Regarding the questions asking to compare the level of ease between the two blocks (see Table 3.4, $C_{pathEasier}$ and $C_{columnsEasier}$), participants did not find the path-following and column tasks to be easier in one condition or another (answers around 4), independently of the Technique.

3.3.4 Additional Analyses

While we did not find that the presence of an avatar affected the number of collisions with the environment, previous studies have shown that people being embodied in an avatar usually tend to avoid obstacles more in the VE [Mestre et al. 2016; Pan and Steed 2019]. Therefore, we decided to explore this effect in more details by analyzing whether the number of collisions could be influenced by the level of embodiment reported by participants. In order to investigate this effect, we computed the correlations (Spearman) between the embodiment questionnaire and the amount of collisions in the FBA condition (as we did not ask embodiment questions in the NA condition). Regarding self-location questions, we found a significant negative correlation between the question $SL_{located}$ and the ratio of shoulder collisions ($r = -0.31, p < 0.05$). We did not find similar correlations for the questions about ownership or agency. This result suggests that people who felt that they were co-located with their virtual body collided less with the environment. Variations

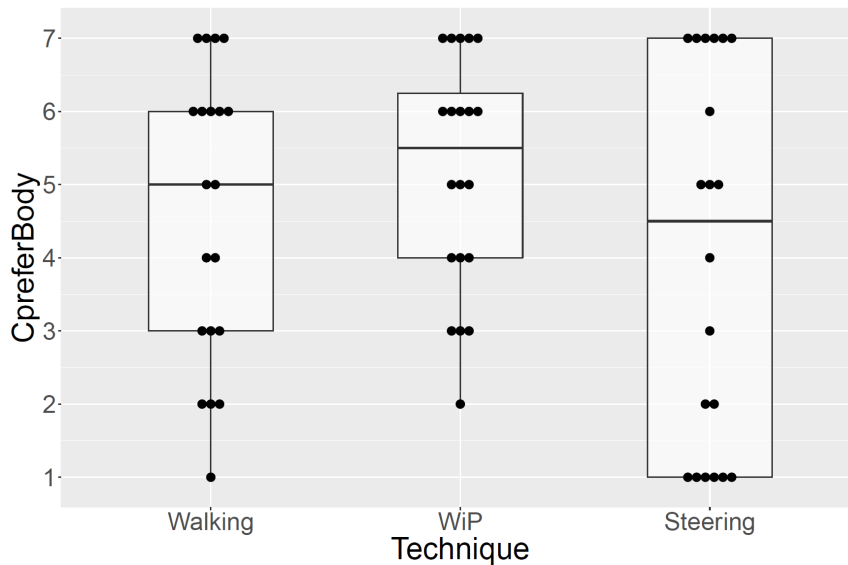


Figure 3.3 – Scores by Technique for the question $C_{preferBody}$; no significant difference between the techniques but a high dispersion for the S condition.

in cybersickness scores over the course of the experiment were not significantly different between techniques ($\chi^2=0.87$, $p=0.65$).

3.4 Discussion

This study explored the potential inter-effects between the use of locomotion techniques and avatars. The first goal was to study the effect of the locomotion technique on embodiment, while the second goal was to explore the impact of the presence of an avatar during navigation, depending on the technique. In this section, we discuss the results on the sense of embodiment, collision avoidance, and finally user preference.

3.4.1 Embodiment

Our first main hypothesis was that the choice of a locomotion technique would influence the sense of embodiment. In particular, we expected high-fidelity locomotion techniques, requiring more physical movements, to elicit a higher sense of embodiment, similarly to previous results on the sense of presence [Slater et al. 1995; Usoh et al. 1999]. Contrary to our expectations, there was no significant difference on the level of embodiment between the locomotion techniques, suggesting that the choice of a technique does

not influence the participants' sense of embodiment.

Two potential reasons may explain this result. A first potential explanation is that participants had a total control over their avatar movements, no matter what technique they used, which has been shown to play a primary role in the sense of embodiment [Fribourg et al. 2020a]. For all tasks, when participants moved, the avatar moved accordingly, therefore there was always a coherence between participants' movements and the feedback. Even for the steering technique, participants had to reorient their body to perform the tasks and were aware of the upper-body motions (e.g. holding the controller in front of them, picking mushrooms). Even though participants were mostly stationary when using the walking-in-place and steering techniques, they still felt a high sense of embodiment, which is consistent with studies in which people embodied avatars even though they were not moving [Galvan Debarba et al. 2017; Kokkinara et al. 2016]. However, contrary to related studies [Kokkinara et al. 2016], the avatar was not necessarily walking in these conditions (especially with the steering technique) in our study. Having an avatar sliding on the ground did not seem to affect participants' sense of embodiment.

A second explanation of our results could be that visual incongruities due to animation quality might have slightly disturbed participants. Even though the difference was not significant, we noticed slightly lower ownership scores in the walking condition, which would be in contradiction with our hypothesis. Because it is the most realistic and high-fidelity technique of locomotion, people may have more expectations in terms of matching between the visual feedback and their proprioception. It is known that the match between visual and motor signals plays an important role in inducing a sense of ownership [Kokkinara and Slater 2014], and that motion artifacts can affect the sense of agency while walking [Koiliias et al. 2019].

In summary, our experiment suggests that total control of avatar movements might contribute more to embodiment than the coherence between avatar movements and camera motion, although artifacts or differences between participants' real movements and the avatar's movements can modulate their sense of embodiment. Further studies will be required to better assess the contribution of the upper-body and lower-body control, as well as the impact of animation artifacts on the sense of embodiment.

3.4.2 Collision Avoidance

Our second main hypothesis was that people would collide less with the columns when embodied in a full-body avatar, however it was not supported by the results. In general,

we observed different behaviours among participants, some avoided obstacles while others went through them. Participants who ignored the columns reported that they did it to pick the mushrooms faster, and because they were not disturbed by going through them, contrary to people who avoided them. This result differs from other studies that have found that people tended to avoid obstacles when they were embodied in a realistic avatar, but these studies used obstacles on the trajectory of the hand [Argelaguet et al. 2016] or at lower height [Pan and Steed 2019]. We believe that the task and the obstacles could explain the difference in our results, as the avatar may have not contributed to avoid the columns. First, the task required participants to focus on finding and picking the mushrooms which could have diverted their attention. Second, the obstacles might not have been close enough to compel the participants to use a body reference to avoid collisions.

3.4.3 Preference

3.4.3.1 Logical and pleasing aspects

We expected that people would find the condition with a full-body avatar more logical and pleasing. For the logical aspect, this was the case for the task involving a mirror. However, some participants reported that the avatar’s movements were sometimes “disturbing”, for example that the knees would bend too much compared to what they were doing. The absence of an avatar was still perceived as less logical, where several participants reported negatively about seeing only controllers in the mirror condition. Participants did not find it significantly more logical to have a full-body avatar in other tasks. This may be due to the fact that most VR applications currently only use floating hands or controllers as virtual representations, and that participants were therefore not surprised by this simpler representation (controllers only). For the pleasing aspect, the results were significant only for the tasks not involving the mirror. Although participants appreciated having a body visible from a first-person perspective, they did not find it more pleasing to see the avatar in the mirror. A potential explanation could be that several participants reported being disturbed by the difference in external appearance (clothes, haircut, morphology) of the avatar compared to their own, yielding lower scores on this question.

3.4.3.2 Preferred condition

There were several questions asking participants whether they preferred the condition with or without an avatar. In particular, we expected that participants would prefer the condition with an avatar, and would find the navigation tasks easier to perform in such cases. The high variance in the answers to the question “I preferred having a body” shows different categories of people. Some participants were really disturbed by an absence of body and preferred having an avatar. Such participants described the experience with adjectives like “realistic” or “immersive” to describe the condition with an avatar. Other subjects did not prefer any of the conditions, or tended to prefer the condition without an avatar, as the avatar could be seen as “an obstacle” or too different from them that it was more disturbing than helping. This could potentially be explained by them being more task-oriented. They described this condition with adjectives like “easy”, “transparent”, “unconstrained” or “less disturbing”.

The most used words for the condition with an avatar were: funny (9), easy (8), disturbing (7), realistic (6), immersive (5) and interesting (5). For the condition without avatar, it was: easy (9), simple (6), interesting (5) and disturbing (5). While adjectives for the condition without an avatar were more focused on tasks achievement (easy, simple), it is interesting to point that positive adjectives related to immersion and realism only appeared in the condition with an avatar. However, while our results show a slight preference for having an avatar in the navigation tasks of our experiment, it is possible that this preference is not directly related to the task but that it might be common to virtual experiences. It would therefore be interesting to explore potential effects of the task on this preference in future studies.

3.4.3.3 Ease of tasks

Similarly to the work by Lugin et al. [2018], the presence of a virtual body to perform the tasks did not seem to impact the user in terms of performance or preference. Similarly to their study using an action-based game, our experiment contained goal-oriented tasks, especially in the columns task. In particular, some participants of our experiment reported that they only needed the controllers to perform the tasks. They therefore seemed to have been more focused on achieving the task, possibly reducing the awareness of the presence of the avatar. For tasks where they had to notice the avatar (mirror task and path-following task mostly), some participants considered the avatar as an obstacle or

an annoyance that was diverting them from the task. Our results need to be considered relatively to the tasks, and other tasks could be tested. For example, tasks which need a body reference and a finer control of the avatar, like the stepping task in the work by McManus et al. [2011], could be investigated.

3.4.4 Limitations

A limitation of this study is related to the degree of realism of the avatars and their animation. For instance, the calibration only adjusted the global scale of the avatar, while other papers studying avatars and collisions used more precise calibrations [Mestre et al. 2016]. Several solutions are now starting to appear to easily and precisely calibrate an avatar to the participants morphology [Pujades et al. 2019], which could help in the future to more accurately measure collisions with the environment. In terms of animation, several participants were also disturbed by the leg movements, especially when physically walking in front of the mirror. It was previously found that offset rotation of joints can affect embodiment [Koiliias et al. 2019]. It could therefore be interesting to run a similar study with higher-quality motion capture systems to evaluate whether differences in terms of embodiment could be influenced by the animation quality in such cases. Still, animating avatars with Inverse Kinematics as performed in this study is a common procedure in such embodiment studies [Roth et al. 2016; González-Franco et al. 2010].

Even though people felt a sense of embodiment while using walking-in-place and steering techniques, some participants noticed that the feedback was strange, especially in front of the mirror. It would be interesting to study different types of visual feedbacks for the techniques. As an example, several studies have started to compare different feedbacks for the walking-in-place technique [Park and Jang 2019; Lee et al. 2020], which can be walking animation, synchronous stepping or running animation.

3.5 Conclusion

The study presented in this chapter explored the interrelations between avatar embodiment and locomotion techniques. The study considered three locomotion techniques requiring different user involvement (walking, stepping in place, limited physical movement) and three main tasks involving a different awareness of the virtual avatar that participants had full control of. Overall, we found that people experienced similar lev-

els of embodiment with the three locomotion techniques and that the coherence of the avatar’s motion with respect to motion of the VE did not create any disruption in the sense of embodiment. Our results represent a first attempt to qualify the interrelations between locomotion and virtual embodiment, and suggest that the locomotion technique used has little influence on the user’s sense of embodiment in VR when users have a full control of their avatar movements. In this experiment, users could see exactly the movements they were performing, but this is not always the case. We mentioned that contrary to locomotion, manipulation techniques have been more studied, but this is less the case for techniques that distort users’ motion. In the next chapter, we will therefore focus on manipulation, and most specifically on anisomorphic manipulation. This type of interaction can impact embodiment as it creates a mismatch between real and virtual motions.

INVESTIGATING DUAL BODY REPRESENTATIONS DURING ANISOMORPHIC 3D MANIPULATION

Abstract: In virtual reality, several manipulation techniques distort users’ motions, for example to reach remote objects or increase precision. These techniques can become problematic when used with avatars, as they create a mismatch between the real performed action and the corresponding displayed action, which can negatively impact the sense of embodiment. In this chapter, we propose to use a dual representation during anisomorphic interaction. A co-located representation serves as a spatial reference and reproduces the exact users’ motion, while an interactive representation is used for distorted interaction. We conducted two experiments, investigating the use of dual representations with amplified motion (Go-Go technique) and decreased motion (PRISM technique). Two visual appearances for the interactive representation and the co-located one were explored.

4.1 Introduction

Many techniques have been invented for VR that increase user performance but distort user motion. While this is not necessarily a problem when using a simple user representation (e.g. a sphere representing the user’s hand), this might cause strange feedback when embodied in a full-body avatar. Nevertheless, representing users with high-fidelity avatars is common as they offer several advantages. Avatars were found to increase spatial awareness [Draper et al. 1996], or even to impact perceived effort during a physical task [Kocur et al. 2020a]. There are also an increasing number of applications using full-body avatars, especially social VR applications. To maximize the sense of embodiment towards avatars, spatially and temporally congruent visuomotor stimulation is an efficient method [Kokkinara and Slater 2014]. However, distorting movements during interaction

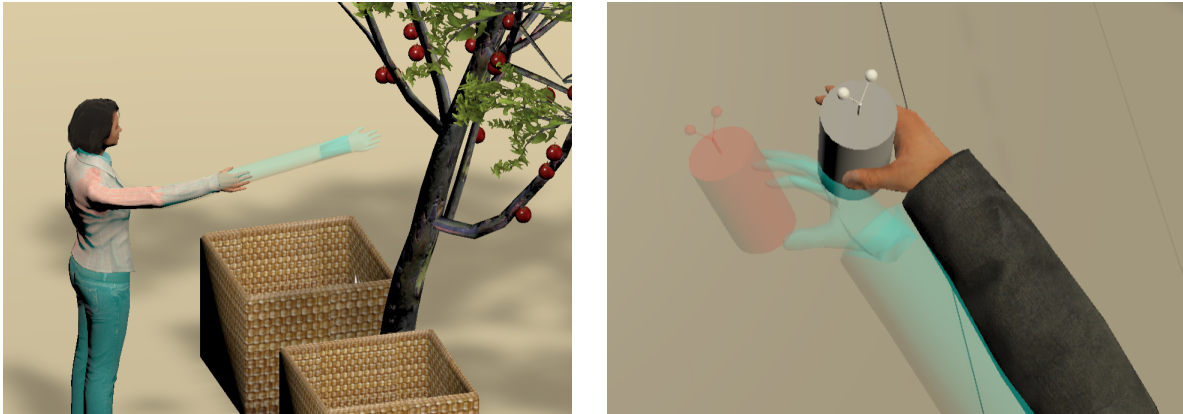


Figure 4.1 – Illustration of two types of dual body representations studied in this chapter. On the left image, a ghost representation enables remote manipulation while a realistic co-located representation provides feedback with respect to the real user’s position. On the right image, a ghost representation provides feedback with respect to the user’s real position while a realistic representation enables precise manipulation with the environment thanks to slowed motion.

could be detrimental to the sense of embodiment, as spatial congruency would not be respected anymore. Also, if the virtual body movements are distorted, users lose the information of their real body position, which might impact their understanding of the interaction technique.

To keep the advantages of both anisomorphic interaction and spatial reference offered by the avatar, we propose to provide the visual feedback of both distorted and real motions by displaying two avatars simultaneously. This type of feedback is referred hereinafter as dual representation, as opposed to single representations where only one avatar shows one type of feedback (real or distorted). The aim of this dual representation is to offer both the feedback of real users’ motions as well as distorted motions during anisomorphic manipulation. In the context of this study, we define the dual representation as made of an interactive representation, used for interaction and displaying altered movements, and a co-located representation displaying real movements. This type of feedback has already been explored in the context of finger collisions with objects for example [Prachyabrued and Borst 2014; Canales et al. 2019], and we believe that it could be valuable to all interaction techniques involving motion distortions to support both the sense of embodiment and interaction capabilities.

In order to evaluate the impact of dual representations on the sense of embodiment and interaction performance, we conducted two within-subject experiments to compare

different user representations (both single and dual) during anisomorphic manipulation. To this end, two common interaction methods were considered: remote manipulation with a gain that increases movement [Poupyrev et al. 1996], and precise manipulation with a gain that decreases movement [Frees et al. 2007]. Both manipulation techniques create offsets between virtual and real hands, by either amplifying or decreasing users' movements. The interactive and co-located representations had either a realistic visual appearance or a transparent/ghost appearance.

This chapter provides insight on which user representation to choose during 3D anisomorphic manipulation.

4.2 Extended and Multiple Body Representations

In the related work of this thesis, we presented common techniques involving motion alterations and the impact they can have on the sense of embodiment (see Section 1.4.2.2). While the precise impact of motion alteration on embodiment is still unclear, several studies showed that a mismatch between users' motion and their virtual avatar was detrimental to embodiment, especially to the senses of agency and self-location. Most of these studies focused on cases where users saw only one virtual representation of their movements. In this chapter, we ask the question: what would happen if they could see multiple representations of their movements during interaction? Few studies have investigated virtual representations with additional body parts or full bodies. In this section, we will present these studies which investigated either extended or multiple body representations, which are a lead to explore to reconcile embodiment and motion alteration.

4.2.1 Extended Body Representations

Avatar extensions have been explored, such as human tails [Steptoe et al. 2013] or third arms [Laha et al. 2016]. These studies used a material reminiscent of a ghost to distinguish the additional part from the rest of the body. They found that people could experience a sense of embodiment towards these additional limbs. Another study investigated the use of an extended arm in augmented reality, while keeping a representation of the real arm [Feuchtner and Müller 2017]. This feedback was less appreciated than only an extended arm, without the real arm. More recently, an appended limb has been used as a spatial reference to extend proprioception and increase target selection [Tian et al.

2020]. This study found that people could feel a sense of ownership towards this limb, especially when they could control and move it prior to the selection task. The authors also tested different transparency levels for the additional limb, and found no impact on selection performance.

4.2.2 Multiple Body Representations

A study investigated the experience of having two bodies in VR, but not spatially co-located neither interacting with the VE [Heydrich et al. 2013]. Similar studies with additional body parts were conducted in real life with the rubber hand illusion [Ehrsson 2009], using video stream [Chen et al. 2018; Guterstam et al. 2020] or augmented reality [Rosa et al. 2019]. More recently, a study investigated “distributed embodiment”, i.e. embodiment towards up to four bodies [Miura et al. 2021]. In this study, participants had split views over four first-person perspectives. The results tended to show that subjects switched attention between bodies, but kept a global parallel sense of embodiment towards all bodies. Another study explored the use of additional hands for interaction, to decrease object selection time but without investigating embodiment [Schjerlund et al. 2021]. Some VR applications have two superimposed representations, but they are usually used for guidance [Yang and Kim 2002] so one representation is not controlled by users. While studies using several controlled bodies often used similar textures for all representations, these guidance applications used a “ghost” metaphor [Yang and Kim 2002], where the second representation used for guidance is more transparent than the main one [Han et al. 2016; Chinthammit et al. 2014].

While people replicated the RHI with two arms or bodies, or used a second representation for guiding users, to our knowledge no study investigated the use of a second representation to show real movements during anisomorphic manipulation. For this reason, we conducted two experiments to explore the embodiment of a dual representation, with two different anisomorphic interaction techniques, involving either amplified or decreased movements.

4.3 Context and Experiments Overview

In this study, we were interested in the potential use of dual representations for interaction in VR. More precisely, the context of this chapter is the use of dual body rep-

representations when there is an offset created between users' real position and the virtual representation position during anisomorphic manipulation. In this context, we consider that dual representations are made of an interactive representation used for interaction with the environment, and a co-located representation showing users' real movements. Therefore, users have control over two avatars simultaneously, but the mapping and visual appearance differ. More precisely, when a motion distortion is applied to a part of the avatar, the hand in our experiments, the two avatars will dissociate, providing visual feedback of both the co-located and distorted motions. When no distortion is applied, a single default representation can be used (a realistic full-body avatar) to maximise embodiment [Martini et al. 2015; Latoschik et al. 2017] and avoid a visual overlap between the two representations. In this paper, when talking about our different experimental conditions, we will always indicate the visual appearance of the interactive representation first (letter on the left), then the co-located representation one (letter on the right). The context is close to the ghost metaphor [Yang and Kim 2002] in which the trainer's movements are superimposed to users' one. However, in our context, users are in control of both representations at the same time.

Dual body representations could be adapted to other situations, but in this study we focus on anisomorphic manipulation techniques. These techniques usually increase or decrease users' motion. In this chapter, we therefore conducted two experiments investigating either amplified motions or decreased motions. The goal was to have two main types of motion alteration. We chose two very well-known manipulation techniques: the Go-Go technique which amplifies movements to reach remote objects [Poupyrev et al. 1996], and the PRISM technique which decreases movements to gain precision [Frees et al. 2007].

4.4 Experiment 1: Dual Representations for Increased Motions During Out-of-Reach Manipulation

The first within-subject experiment investigated the use of a dual representation when interacting with remote objects using the well-known Go-Go technique [Poupyrev et al. 1996]. When using this technique, users' movements above a certain threshold are amplified, enabling both close and remote object manipulation.

4.4.1 Participants and Apparatus

Twenty-four participants (age min=20, max=36, avg=25.0±4.1, 11 women and 13 men) took part in this experiment. On a 7-point Likert scale, 7 of them were VR experts (score equal to or greater than 6), 6 were knowledgeable (score between 3 and 5) and 11 were beginners (score equal to or lower than 2). The majority of participants were students and staff recruited on our campus. All participants gave written and informed consent. The study conformed to the declaration of Helsinki, and was approved by the local ethical committee. Participants did not receive any compensation. They all had a normal or corrected vision.

Participants were equipped with a Valve Index Head-Mounted Display and Knuckles enabling finger tracking, tracked by two base stations. The experiment was developed using Unity 2019.4.12f1. We used gender-matched avatars from the Rocketbox library. They were animated using the RootMotion Final IK plugin. For object interaction (selection and hand poses), we used the SteamVR interaction system.

4.4.2 Go-Go Technique Implementation

Our implementation is based on the original Go-Go implementation [Poupyrev et al. 1996]. A one-to-one mapping is applied until the real hand position R_r reaches a threshold value D , then it becomes non-linear. The virtual hand position R_v is determined as follows:

$$R_v = \begin{cases} R_r & \text{if } R_r < D \\ R_r + k(R_r - D)^2 & \text{otherwise} \end{cases}$$

The threshold D was $2/3$ of the real arm length. The factor k was computed to ensure that the maximum arm length was four times the real arm length. Therefore, when users had their real arm fully extended, the virtual arm was four times longer than their real arm. This k value enabled users to perform the task by reaching all the targets, while maintaining a relatively accurate interaction. To extend the arm, users' motion direction needed to be known. There are several ways of determining it, depending on whether the head, the shoulder or the controller positions are used to compute the direction vector. Different ways were tested, and finally the normalised vector linking the shoulder position to the controller position was kept, similarly to the implementation by Feuchtnner and Müller [2017]. This was the most stable solution, as it did not depend on the head orientation.

4.4.3 Tasks

4.4.3.1 Main Experimental Task: Picking and Sorting Apples

The Go-Go technique uses an adaptative gain, enabling both close and remote interaction. An ecological task involving both interaction in the peripersonal (close to the body) and the extrapersonal (far from the body) space was necessary. We chose the ecological task of picking apples. Participants were facing a virtual tree containing 20 apples (see Figure 4.1). They had to extend their arm to reach the apples placed in their extrapersonal space and pick them. Then, there was a sorting task. Participants had to bring back the apple to their peripersonal space to inspect it. They needed to look at them to see if they were flawless, or rotten, i.e. with stains on them. The goal was to make participants bring the apples back to them, to interact closer to their body and be aware of their dual representation. After looking at the apples, they had to put them in the appropriate basket situated just outside their peripersonal space beside the tree (flawless apples in the left basket, or rotten apples in the right basket). To pick/release the apples, subjects had to grab/release the Knuckles handle. When they grabbed the handle, this would snap the apple to the virtual hand and trigger a hand pose.

4.4.3.2 Additional Task: Maximum Reach Estimation Task

Interacting with remote objects can alter the mental arm representation, and give a sensation of real elongated arm [Feuchtner and Müller 2017]. We therefore decided to add a task to estimate whether the perceived maximum reach distance was influenced by the Representation. For this additional task, participants were immersed in an empty scene, with only the Unity default skybox. They had no virtual body during this task and only saw a red virtual sphere in front of them. They were instructed to move this virtual sphere using the Knuckles controllers' pad to place them at the distance where they thought they could reach it with their arm fully extended. They had to keep their arms at their sides during the measure. This measure was repeated six times, three times with the sphere coming from away (at a distance of twice users' real arm length), and three times from near participants (at a distance of 0.3 times the real arm length), alternatively.

4.4.4 Experimental Design and Protocol

This experiment had a within-subject design with Representation as the independent variable. For each level of Representation, distorted (interaction) motions and real motions could be represented either by a realistic body (R), a ghost body (G) or nothing (\emptyset). For this experiment we chose three levels of Representation, defined as : R - \emptyset , R - G and G - R (see Figure 4.2). In R - \emptyset , only distorted motions were represented with a realistic elongated arm. In R - G, a realistic elongated arm was used for interaction, while real motions were represented by a ghost transparent arm. G - R corresponded to the opposite combination. We did not use other possible combinations, as the goal was to always have a different visual appearance for interactive and co-located representations (so for example the R - R combination was excluded), and only a realistic appearance when using a single representation (therefore no single ghost extended arm). Also, when using the Go-Go technique, the user must see where the virtual hand is to be able to interact during motion distortion, therefore combination \emptyset - R could not be used in this experiment. The order of the different Representations was fully counterbalanced.

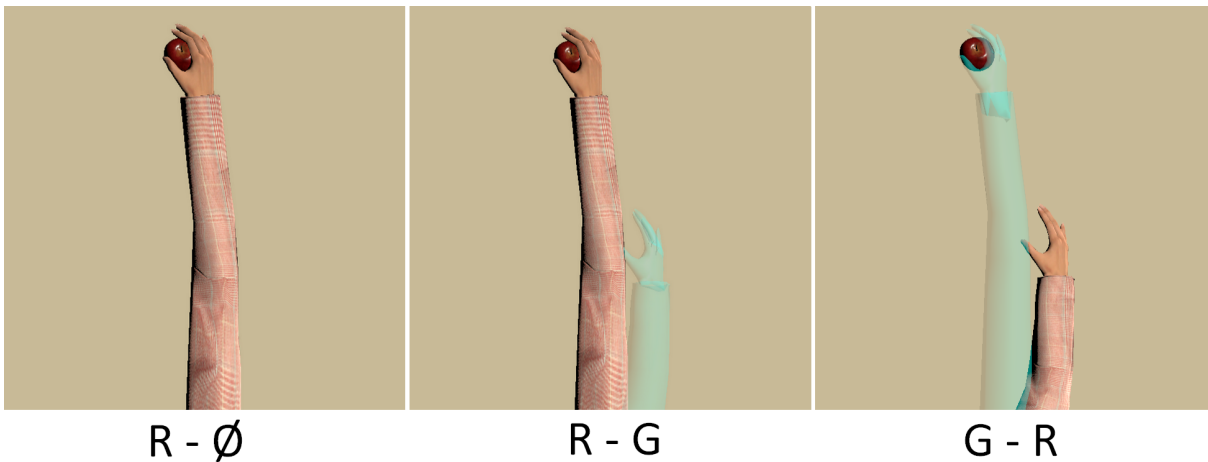


Figure 4.2 – The three levels of Representation in the first experiment with amplified motion. The interactive arm is either realistic (in R - \emptyset or R - G) or transparent (in G - R). When a co-located arm is displayed, a realistic representation (in G - R) or a ghost one (in R - G) is used.

Participants were first welcomed, the experiment was explained to them and they had to read and sign the consent form. Before starting the main experiment, users were first immersed in the experimental scene but without any task to perform. They were represented by an avatar with a global scale calibrated to match their height. They were

immersed 45 seconds to look at the scene and their avatar. The goal was to have a first perception of the virtual scene, with a normal calibrated avatar without extendable arms. After the 45 seconds, they performed the maximum reach estimation task. After this first exposure, the main experiment began, which was divided into three blocks, one for each Representation. Before the experimental task began, they had 20 seconds of free exploration of their avatar and the environment. Then, they had to press the controller’s trigger to start a training with only five apples. After pressing again the trigger, they could start the main task, with 20 apples. The apples were placed similarly in all conditions to be able to compare results between the different representations. At the end of each block, participants were placed in another scene to do the maximum reach estimation task. In total, the experiment session lasted around 50 minutes.

4.4.5 Experimental Data

4.4.5.1 Subjective Measures

Participants’ sense of embodiment was measured using the questionnaires from Peck and Gonzalez-Franco [2021] (mentioned as PGF questionnaire hereafter) and from Roth and Latoschik [2020] (mentioned as RL questionnaire). We decided to use both questionnaires because they have complementary questions. The questionnaire items were evaluated on a 7-point Likert Scale from 1 (Strongly disagree) to 7 (Strongly agree). For the PGF questionnaire, we customised question R7 as recommended in their paper. We used the question “I felt as if my real arm were becoming longer”. For question R8, we asked “I felt a realistic sensation in my body when I saw my virtual body” as recommended. For R14 to R16, we used apples as the source of touch. We thought it would be clearer for participants than asking about the touch of the ground as recommended in the questionnaire paper. It is possible to consider that the passive haptic feedback provided by the Knuckles grip could elicit a sensation of touch, even though the shape was different from an apple.

In addition, six questions specific to this study were added. For the two conditions with a dual representation, questions related to senses of ownership and agency (from the RL questionnaire) were added for both virtual representations, the realistic (opaque) and the ghost (transparent) representations (see Table 4.1). We used the words opaque and transparent to have neutral words describing the representations that would not bias participants’ responses.

Five questions on the global opinion regarding the virtual representation as well as usability were asked (see Table 4.2). Subjects were also asked to rank the conditions in order of preference after the experiment, and to explain why they chose this order.

Table 4.1 – Additional embodiment questions asked after conditions involving a dual representation (in R - G and G - R).

ID	Question
wasMyBodyOpaque	I felt like my opaque representation was my body.
wasMyBodyTransparent	I felt like my transparent representation was my body.
controllingOpaque	I felt like I was controlling the movements of my opaque representation.
controllingTransparent	I felt like I was controlling the movements of my transparent representation.
causingOpaque	I felt like I was causing the movements of my opaque representation.
causingTransparent	I felt like I was causing the movements of my transparent representation.

Table 4.2 – Questions on user experience asked after all the conditions.

ID	Question
liked	I liked my virtual representation(s).
disturbing	My virtual representation(s) was/were disturbing.
easy	It was easy to interact.
clear	It was clear how I could interact with the environment.
exciting	It was exciting to interact with the environment.

4.4.5.2 Objective Measures

Because previous studies showed a possible impact of the virtual representation on performance [Tran et al. 2017], we included a performance measure in this experiment by measuring the time to pick the 20 apples. Similarly, related work showed that having a virtual extended arm can impact arm length perception, because it alters body schema [Kilteni et al. 2012b]. We therefore included the maximum reach estimation task described in Section 4.4.3.2 after each main task, to evaluate whether the virtual representation would impact maximum reach perception.

4.4.6 Hypotheses

Previous studies showed that from a certain length (four times the real arm length), an extended arm do not feel like the users' own arm anymore [Kilteni et al. 2012b]. Reminding users of their real arm might help to create a global sense of embodiment towards their representation, which could be higher than having only one visible arm. Also, having the constant feedback of their own arm might be good for the sense of agency, as they can always see a congruent feedback of their real actions, which is an important factor in eliciting a sense of agency [David et al. 2008]. Therefore we propose as first hypothesis that **dual body representations influence the sense of embodiment, especially the sense of agency (H1.1)**.

While some studies suggested that additional visible information can impact performance [Tran et al. 2017], we hypothesised that seeing real movements could help to understand the transformation applied in the case of anisomorphic manipulation. This should not be enough to increase performance in the case of the Go-Go technique, as the technique is simple and the task we used does not necessitate precision. We hypothesised that **we should not observe differences in terms of performance between the conditions (H1.2)**, as dual representations should not hinder the task.

When using a single representation, an offset is created between the remote virtual hand interacting with objects and the real hand. Because of this mismatch between real and virtual movements, users might get frustrated. On the contrary, having a dual representation lets users see both their real and virtual movements, we hypothesised that this type of representation would be preferred. Also, it could be perceived as fun to embody two different virtual representations. Our third hypothesis was therefore that **people prefer having a dual representation (H3.1)**.

4.4.7 Results

Considering the ordinal nature and the non-normal distribution of subjective questionnaires scores, we performed Friedman non-parametric tests (with $\alpha = 0.05$) on the different embodiment components and the user experience questions, followed by post-hoc pairwise Wilcoxon signed-rank tests with Bonferroni correction. For objective measures, we used a one-way repeated measures ANOVA and Tukey's post-hoc tests when the normality assumption was verified by the Shapiro-Wilk test (for the estimated maximum reach distance), and Friedman tests followed by Wilcoxon tests when the normality as-

sumption was not verified (for the time completion). For the additional questions on realistic and ghost representations in G - R and R - G, we performed Wilcoxon signed-rank tests.

4.4.7.1 Sense of Embodiment and Preference

Embodiment questionnaires For the RL questionnaire, we computed the global scores for the three components (Ownership, Agency and Change) as recommended. Globally, the Ownership ($Mdn = 5$, $IQR = 3.44 - 5.81$) and Agency ($Mdn = 6$, $IQR = 5.75 - 6.5$) scores were high in all conditions while the Change ($Mdn = 2.25$, $IQR = 1.25 - 3.75$) scores were very low. For all components, we did not find any significant difference.

For the PGF questionnaire, we also computed global scores for each component (Ownership, Appearance, Multi-Sensory and Response), as well as the Multi-Sensory sub-score, the Agency score, using the two questions directly related to the sense of agency. Components scores were globally low ($Mdn = 3.75$, $IQR = 3 - 4.67$ for Ownership, $Mdn = 2.63$, $IQR = 1.75 - 3.41$ for Appearance, $Mdn = 3.42$, $IQR = 2.67 - 4.17$ for Multi-Sensory, $Mdn = 2.75$, $IQR = 2 - 3.83$ for Response and $Mdn = 4$, $IQR = 3.5 - 5$ for the Agency sub-component), with common questions getting relatively high scores (such as *I felt like I could control the virtual body as if it was my own body* or *I felt as if my body was located where I saw the virtual body*) while questions not adapted to the experimental protocol gave very low scores (such as questions on tactile sensations). For the Response component, there was a main effect of Representation ($\chi^2 = 7.525$, $p < 0.05$). The Kendall's W value showed a small effect ($W = 0.16$). Pairwise tests showed that the score for R - \emptyset was significantly higher than for G - R ($p = 0.01$). This seemed mostly influenced by the question *I felt a realistic sensation in my body when I saw my virtual hand*. For the Multi-Sensory component, Friedman's test showed a main effect of the Representation ($\chi^2 = 6.1$, $p < 0.05$), but the pairwise test did not reveal any significant difference between the conditions. The results of these two components are visible in Figure 4.3.

Additional questions For the additional ownership and agency questions about the realistic and the ghost representations (G - R and R - G only), there were significant differences in agency questions scores between R - G and G - R (see Figure 4.5). For the question *controllingOpaque*, the scores were significantly higher in R - G than G - R ($p < 0.05$). Participants felt more in control of the realistic arm when it was used for interaction than when it was displaying real motions. For the question *controllingTrans-*

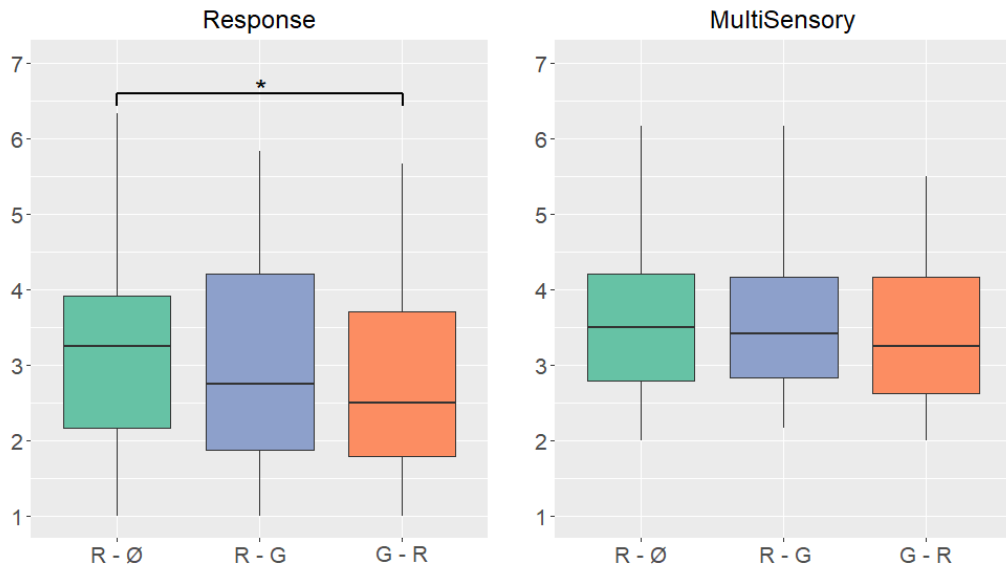


Figure 4.3 – Results for the two components Response and Multi-Sensory from the PGF questionnaire in Experiment 1, for which a main effect of Representation was found. Only the pairwise test on the Response component showed a significant difference between R - ∅ and G - R ($p < 0.05$). There was no main effect for other components.

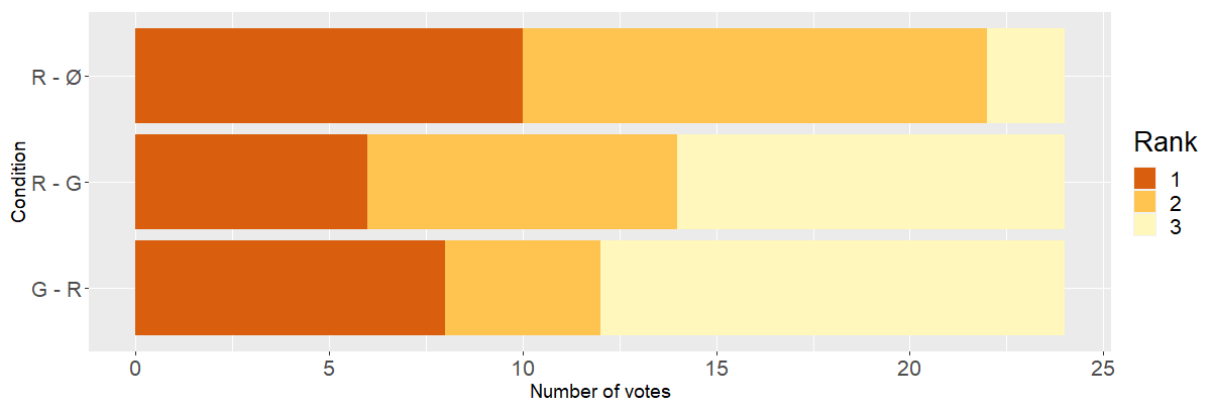


Figure 4.4 – Ranking for the different conditions in the Go-Go experiment. R - ∅ was preferred with 10 participants ranking it as first, followed by R - G and finally G - R.

parent, the scores were significantly higher in G - R than R - G ($p < 0.01$). Similarly to the realistic arm, control was higher when interacting with the ghost arm. For the question *causingTransparent*, the scores were significantly higher in G - R than R - G ($p < 0.01$). No significant difference was found for the questions on ownership. We compared scores for similar types of representation (interactive or co-located) depending on the visual appearance. The scores for the interactive representations were not significantly different between the two appearances, neither for the co-located appearance. For each dual representation condition, we also looked at the potential difference in the scores between the interactive and the co-located representation. For the *controlling* and *causing* questions, scores were significantly higher for the realistic extended arm than for the ghost short arm in R - G ($p < 0.05$).

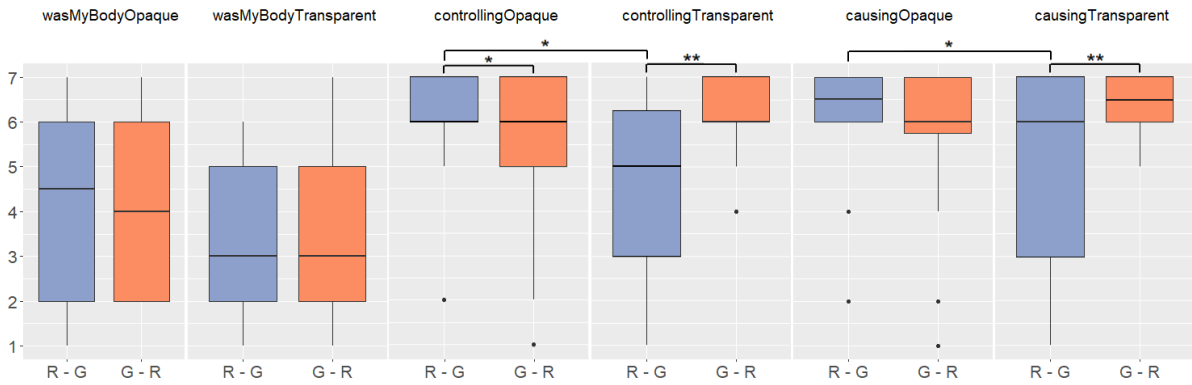


Figure 4.5 – Results of additional questions on the senses of ownership and agency for G - R and R - G in the experiment with the Go-Go technique. * $p < 0.05$, ** $p < 0.01$

Preference R - \emptyset was the preferred condition, with 10 participants ranking it as their most preferred condition (see Figure 4.4). Its average rank was 1.67. R - G and G - R had the same average rank equal to 2.17. There was no significant difference on the user experience questions. The scores were average for the question *liked* ($Mdn = 4$, $IQR = 2.75 - 6$), low for *disturbing* ($Mdn = 2$, $IQR = 1 - 5$), high for questions *easy* ($Mdn = 6$, $IQR = 5.75 - 7$), *clear* ($Mdn = 6$, $IQR = 6 - 7$) and *exciting* ($Mdn = 6$, $IQR = 6 - 7$).

4.4.7.2 Objective Measures

For the mean estimated maximum reach distance, corresponding to the average of the six measures from the maximum reach estimation task, the sphericity was violated so a Greenhouse-Geisser correction was applied. We found a main effect of Representation

($F_{2,37,54.52} = 10.48$, $p < 0.001$, $\eta_p^2 = 0.313$). Post-hoc test showed that the baseline (the measure prior to the experiment) was significantly lower than measures after the different levels of Representation, as all the pairs with the baseline in them had a p-value lower than 0.001. However, there were no differences between the three levels of Representation. In the baseline, the estimated maximum reach was equal to $83.4 \pm 15.2\%$ of the real arm length. After the different conditions, it was respectively equal to $91.7 \pm 16.2\%$ of the arm length after R - \emptyset , $89.9 \pm 16.9\%$ after R - G and $90.6 \pm 16.9\%$ after G - R. We did not observe any order effect.

There was also no significant difference in the time completion between the different blocks. People took 105.7 ± 40.7 seconds in average in condition R - \emptyset , 96.6 ± 25.3 seconds in R - G and 99.3 ± 22.8 seconds in G - R.

4.4.8 Discussion

The main goal of this experiment was to explore the impact of dual representations on the sense of embodiment and user performance. Except for a difference on the Response component between R - \emptyset and G - R, embodiment scores did not highlight differences between the conditions, which does not support H1.1. Additional questions showed that for both visual appearances, people had a higher sense of agency towards the arm when they were interacting with it (even if it was sometimes extended), than when the arm was showing their real movements. This is interesting as it encourages to introduce more interaction tasks in future embodiment studies, to study its impact on embodiment and potentially increase embodiment towards deformed avatars. Also, the agency scores for the ghost arm were significantly lower than the realistic arm in R - G. The opposite was not true in G - R. This means that participants could feel control over a ghost extended arm because they were interacting with it, but they felt less control over a co-located ghost arm while interacting with a realistic extended arm.

Additionally, the maximum reach estimation task revealed an increased perceived maximum reach distance after all the conditions, compared to the measure prior to the experiment. This shows that interacting with an extended arm changed users' mental representations of themselves, and they perceived their real arm to be longer. This is similar to results found in other studies [Feuchtner and Müller 2017; Lin et al. 2020].

Regarding user performance, we did not observe any significant difference in task completion time, which does not contradict H1.2. Participants performed similarly under all conditions. This is probably due to the fact that the co-located representation did not

interfere during the task, as it was only an additional information not located where the manipulation was happening.

Almost half of participants preferred using only one representation, which does not support H1.3. They found it more “playful”, or that knowing only where the interactive hand is was “the most important”. Several participants also reported it as more “realistic” because they only had one arm, even though this arm was extended. This is in line with the study by Feuchtner and Müller [2017] that also considered an extendable arm in augmented reality, in which 67% of participants preferred not seeing their real arm, and could embody the extended arm when interacting with it. Still, some participants preferred having a dual representation, to have the information of their real arm position. Some of them preferred their real body represented by a realistic body. These participants considered the ghost arm as an “extension”, a superpower they had in the VE. Other people preferred interacting with a realistic arm, as they felt they were not able to pick apples with an “intangible” arm, and were more precise with a realistic arm. These two opposite opinions explain the similar mean ranking for R - G and G - R. Even though the single representation was preferred, there seems to be some individual differences.

The results could also be greatly influenced by the type of mapping. For this reason, we conducted a second study investigating another type of motion distortion.

4.5 Experiment 2: Dual Representations for Decreased Motions During Precise Manipulation

The goal of the second within-subject experiment was to investigate the use of a dual representation when forced to be always in sight during a task in the peripersonal space. We also wanted to test a technique with a different type of gain, i.e. decreasing users’ movements. The PRISM technique was chosen as it scales down users’ movements to increase precision.

4.5.1 Participants and Apparatus

In this second experiment, we also had 24 participants (age min=22, max=36, avg=26.8±3.3, 12 women and 12 men). None of them did the first experiment. 4 of them were VR experts, 13 were knowledgeable and 7 were beginners.

The apparatus was the same to that in the first experiment.

4.5.2 PRISM Technique Implementation

The PRISM technique adjusts the virtual hand motion (translation and rotation) depending on users' hand speed. For translation, we scaled users' motion depending on the speed measured in m/s . For rotation, the scale depends on the angular speed in $degree/s$. When implementing PRISM, the gains can be applied on global translation/rotation or independently on each axis. In our experiment, we used global scaling as it was found more intuitive after several tests. The different cases determining the gains applied are described here. The threshold values $MinV$, SC and $MaxV$ were empirically adjusted to our task and its difficulty.

- $HandSpeed < MinV$. In this case, the motion is considered as noise and not intentional motion. We used $MinV = 0.01m/s$ for translation and $MinV = 5 degree/s$ for rotation.
- $MinV < HandSpeed < SC$. Users are performing a slow motion in order to be precise. The function determining the gain applied is linear (going from 0 for $MinV$ to 1 for SC). We used $SC = 0.1m/s$ for translation, and $SC = 50 degree/s$ for rotation.
- $SC < HandSpeed < MaxV$. In this case we use a one-to-one mapping. We chose $MaxV = 0.2m/s$ for translation and $MaxV = 60 degree/s$ for rotation.
- $HandSpeed > MaxV$. This case shows an intention to remove the current offset created between the virtual hand and the real hand. When the speed is greater than $MaxV$, the offset is instantly recovered.

4.5.3 Task

The task was similar to the 6-DOF task considered by Frees et al. [2007]. Subjects were instructed to grab a 3D object and place it at a given target position. The object was a cylinder, to have a simple hand pose to grab it, with an antenna on top of it to constrain its rotation on the three axes. The target consisted of the same object but transparent and red (see Figure 4.1). When the object was correctly placed, it turned green. The object was considered well placed when its centre was within 3 millimetres of the target's centre and its three axes of rotation were aligned with those of the target (with a tolerance of 2.25 degrees per axis). The objects were always shown in the same order across the different conditions.

4.5.4 Experimental Protocol and Design

Similarly to Experiment 1, the experiment followed a within-subject design with Representation as the independent variable. This variable had four levels (see Figure 4.6). We added a fourth condition, \emptyset - R, because the PRISM technique is compatible with having only the real movements displayed and the object slowed down, contrary to the Go-Go technique. The order of the different Representation conditions was counterbalanced using a 4×4 Latin square design.

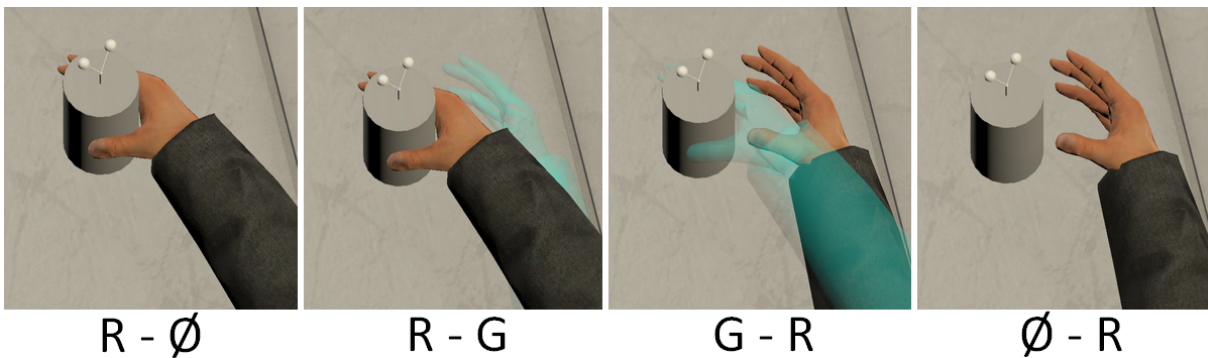


Figure 4.6 – Different levels of Representation in the second experiment with amplified motion. The interactive arm is either realistic (in R - \emptyset or R - G), transparent (in G - R) or not displayed (in \emptyset - R). A co-located arm is displayed, either a realistic one (in G - R and \emptyset - R) or a transparent one (in R - G).

Participants were first welcomed, the experiment was explained to them and they had to read and sign the consent form. Then they were immersed in the VE where they first had 20 seconds to observe their virtual body and the environment. Then, they had to press the controller's trigger to start a training with only two objects to place. They had a maximum of 30 seconds to place each object after which they could start the main experiment by pressing again the trigger. They had three minutes to place as many objects as possible. In order to keep the exposure time the same for each condition, we preferred to fix the total exposure time because we expected stronger user variability in this task than in the first experiment task. The next object (and the associated target) would appear when the previous one was correctly placed. In total, the experiment session lasted about an hour.

4.5.5 Experimental Data

We used the same subjective questionnaire as in Experiment 1. Only the following questions were changed, in the PGF questionnaire:

- R7: I felt as if my body *had changed*
- R14: It seemed as if I felt the touch of the *virtual objects* in the location where I saw the virtual body touched
- R15: It seemed as if the touch I felt was caused by the *virtual objects* touching the virtual body
- R16: It seemed as if my real body was touching the *virtual objects*

As objective data, the number of completed placements was counted. The times when each object was displayed, picked, released and correctly placed were logged. The hand velocity (in m/s) as well as the offset between the virtual and the real hands were also saved at each frame, for both left and right hands.

4.5.6 Hypotheses

We globally had the same hypotheses as in the first experiment. This experiment was slightly different from the first one, both because the technique decreased users' movements and the interaction was happening in users' peripersonal space. The PRISM technique alters users' movements which creates an offset between the real and the virtual hands [Farrer et al. 2008]. Yet, compared to the Go-Go technique, the offset introduced will tend to be smaller and will also increase progressively during the manipulation process. On the one hand, as the offset increases progressively and will tend to be small, the chances of noticing the offset are reduced. On the other hand, as the offset is dependent of the motion speed, the user might perceive the virtual hand motion as unpredictable. The dual representation could enable to decrease this effect of control loss. However, having two bodies with different mappings in the peripersonal space could be disturbing for users. One hypothesis was that **dual representations influence the sense of embodiment, especially the sense of agency (H2.1)**.

We were still expecting similar performance between the different conditions. Because in all the dual representation conditions one representation is semi-transparent, we hypothesised that it would not add too much visual information to affect performance, so that **we should not observe differences in terms of performance between the conditions (H2.2)**.

Finally, because with dual representations there would be two virtual hands very close to each other, we were expecting a less pronounced preference for dual representations compared to the Go-Go technique, but still a preference because it would not result in any loss of information about users' movements. The third hypothesis was that **people would slightly prefer having a dual representation (H2.3)**.

4.5.7 Results

We performed a similar analysis to Experiment 1. Subjective data were analysed using Friedman's tests and objective measures using either one-way repeated measured ANOVA or Friedman's test depending on the Shapiro-Wilk test significance.

4.5.7.1 Sense of Embodiment and Preference

Embodiment questionnaires No significant effect of Representation on the components from the RL questionnaire was found. Ownership ($Mdn = 4.625$, $IQR = 3 - 5.5$) and Agency ($Mdn = 5.125$, $IQR = 4 - 6.062$) were above average. The Change component scores were low ($Mdn = 2$, $IQR = 1 - 3.062$). Interestingly, the question *It felt like the virtual body was my body* was influenced by Representation ($p < 0.05$), with single representations having better scores than dual representations, and the pairwise tests showing that $\emptyset - R$ was significantly higher than $G - R$. Other questions had similar results between Representations, resulting in no significant difference in the Ownership component.

For the PGF questionnaire, components for which we found a main effect of Representation are shown in Figure 4.7. Components scores were globally average ($Mdn = 3.83$, $IQR = 2.67 - 4.67$ for Ownership, $Mdn = 3.13$, $IQR = 2.13 - 3.5$ for Appearance, $Mdn = 3.5$, $IQR = 2.96 - 4.38$ for Multi-Sensory, $Mdn = 3$, $IQR = 2 - 3.67$ for Response and $Mdn = 4$, $IQR = 3 - 5$ for Agency). For both the Response ($\chi^2 = 8.85$, $p < 0.05$) and the Ownership ($\chi^2 = 8.38$, $p < 0.05$) components, Friedman's test showed a main effect of the Representation. $R - \emptyset$ had higher scores but the pairwise tests did not reveal any significant difference between the conditions. However, the question *I felt as if my body was located where I saw the virtual body* was significantly higher in $R - \emptyset$ compared to $R - G$ and $G - R$. Even though there was an offset with their real hand, participants felt co-located with their avatar. There was also an effect of Representation on the question *I felt that my own body could be affected by the virtual world*, with $R - \emptyset$ having significantly higher scores than $R - G$. Friedman's test showed a main effect of the Representation on the

global embodiment score ($\chi^2=9.63, p<0.05$). Embodiment score in R - \emptyset was significantly higher than in R - G ($p < 0.05$). There was no other significant difference.

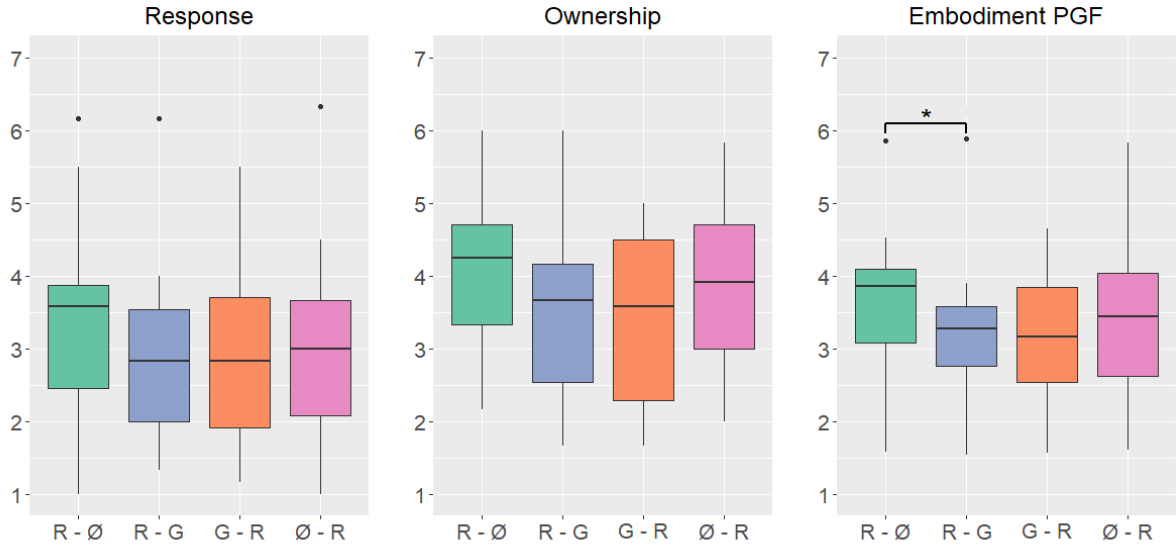


Figure 4.7 – Results for the two components Response and Ownership, as well as the global Embodiment score (from the PGF questionnaire) in Experiment 2, for which a main effect of Representation was found. Only the pairwise test on Embodiment scores showed a significant difference between R - \emptyset and R - G ($p < 0.05$). There was no main effect for other components.

Additional questions For the additional questions, we did not find any significant difference (see Figure 4.8). But, we also compared the scores between each similar question (for example, *controllingOpaque* and *controllingTransparent*). The scores for the question on controlling the interactive representation (i.e. showing distorted motions) were higher with the realistic appearance (in R - G) than with the ghost appearance (in G - R) ($p < 0.05$). The scores for the question *wasMyBody* for the interactive representation were also higher with the realistic texture (in R - G) than with the ghost texture (in G - R) ($p < 0.05$). In G - R, the scores for *wasMyBody* and *controlling* were significantly higher for the co-located realistic arm than for the ghost interactive arm ($p < 0.01$).

Preference R - \emptyset was the preferred condition, with 13 participants ranking it as their most preferred condition (see Figure 4.9). Its average rank was 1.92. R - G came second with an average rank of 2.38, then \emptyset - R (2.58) and G - R (3.13) as the least preferred.

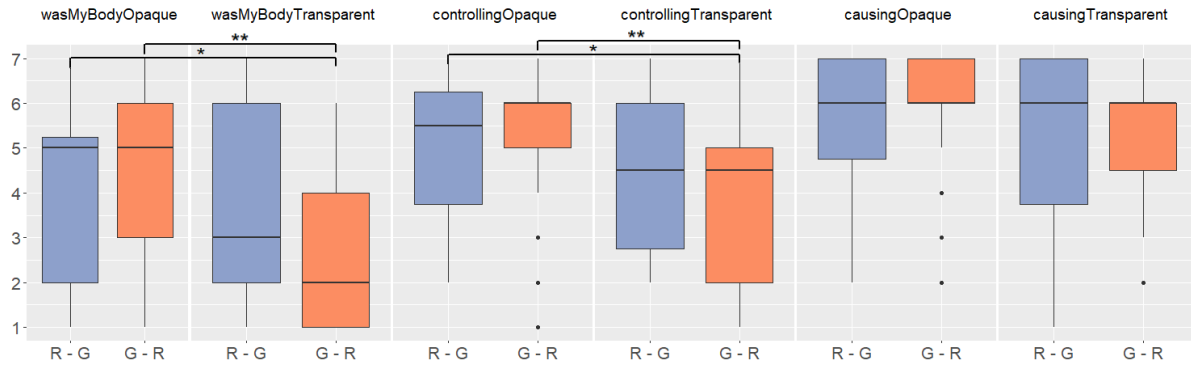


Figure 4.8 – Results of additional questions on the senses of ownership and agency for G - R and R - G in the experiment with the PRISM technique. * $p < 0.05$, ** $p < 0.01$

There was no significant difference in the responses to user experience questions, similarly to Experiment 1. The scores were average for the question *liked* ($Mdn = 4$, $IQR = 2.75 - 5$), between low and average for *disturbing* ($Mdn = 3$, $IQR = 2 - 5$), high for questions *easy* ($Mdn = 5$, $IQR = 3 - 6$), *clear* ($Mdn = 6$, $IQR = 5 - 7$) and *exciting* ($Mdn = 6$, $IQR = 5 - 7$).

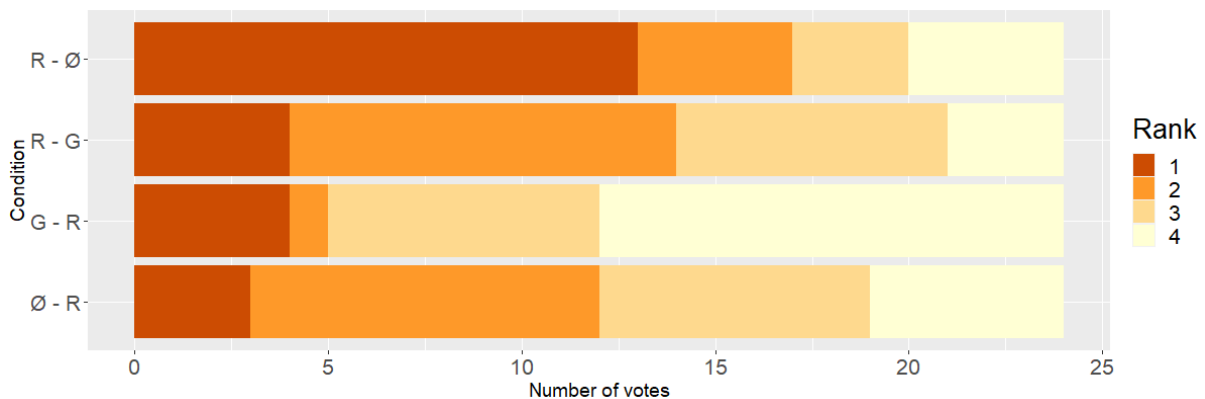


Figure 4.9 – Ranking for the different conditions in the PRISM experiment. R - ∅ was preferred with 13 participants ranking it as first.

4.5.7.2 Objective Measures

The number of completions was slightly higher in R - ∅ but no significant difference was found between the four conditions ($F_{2.76,60.63} = 2.43$, $p = 0.079$, $\eta_p^2 = 0.100$). People correctly placed 15.7 ± 4.9 objects in average in R - ∅, 13.4 ± 6.0 in G - R, 13.5 ± 5.1 in R - G and 13.3 ± 5.3 in ∅ - R. We also counted the number of adjustment releases (when objects were released without being correctly placed), for which there was a significant

effect of Representation ($p < 0.01$). Pairwise tests showed that the number of adjustment releases was significantly higher in \emptyset - R than in R - \emptyset . The average number of adjustment releases was equal to 15.8 ± 7.0 in R - \emptyset , 16.4 ± 9.5 in G - R, 15.3 ± 7.8 in R - G and 19.7 ± 7.4 in \emptyset - R. Also, neither the offsets created nor the hand velocity were significantly different between the conditions. The average offset was $3.39 \pm 0.97\text{cm}$.

4.5.8 Discussion

The goal of this second experiment was to study the influence of dual representations on embodiment and performance when the interaction took place in the peripersonal space. We expected embodiment scores to be higher with the dual representations. On the contrary, there was a tendency of higher scores in R - \emptyset but pairwise tests could not show significant results. Only the global embodiment score showed that embodiment in R - \emptyset was higher than in R - G. Indeed, participants reported being disturbed by the presence of two hands, which could explain this result. Between the two dual representations, the results on the sense of embodiment tended to show that in this experiment, the hand appearance (realistic versus transparent) had an impact. The scores for the questions about control and ownership were higher with the realistic hand appearance than with the ghost one.

We did not find a significant difference between the conditions for the performance measure (number of completions), which does not contradict H2.2. However, performance tended to be higher for R - \emptyset , and equivalent for dual representations and the single representation \emptyset - R. We also reported that the number of adjustment releases was high in \emptyset - R. It was indeed observed during the experiment that in this condition, where the hand would cross the object when there was an offset, people would tend to release and grab again the object to remove the offset. This is in line with papers showing that users are disturbed by interpenetrations [Canales et al. 2019].

Also, the preference for condition R - \emptyset was slightly clearer than in the first experiment. But interestingly, R - G was often ranked second, showing a good acceptance of the ghost hand to show real movements. Some participants reported that it was easier to understand their virtual movements when they had two representations. The dual representation also enables keeping the contact between a virtual hand and the virtual object. This is different from the original PRISM implementation [Frees et al. 2007] where the virtual representation moves away from the object (like \emptyset - R in our experiment), and the offset is represented by either a line between the hand and the object for translations, or two

sets of 3D axes for rotations. Our visual feedback is more compatible with avatars, as it leverages avatars to represent the offset.

4.6 General Discussion

This section gives global discussion on the two experiments with some leads of future studies.

4.6.1 Impact of Dual Body Representations on Embodiment and Performance

Embodiment scores for dual representations were globally similar to the scores for single representations, especially when using the Go-Go technique. This tends to show that having two bodies still elicited a good global sense of embodiment, which is in line with previous studies [Chen et al. 2018; Miura et al. 2021]. While we expected that showing real movements would increase the sense of agency, it was not higher compared to conditions when people could only see their distorted movements. This is in accordance with other studies which showed that people are not disturbed by small offsets [Porssut et al. 2019; Kokkinara et al. 2015] or can embody an extended arm until a certain length [Kilteni et al. 2012b; Feuchtner and Müller 2017]. People even felt more in control of the extended arm than of the arm showing their real movements. But in the second experiment when the interaction happened in the peripersonal space, the avatar visual appearance seemed to have a higher impact on agency. Both virtual representations were visible and closer during object manipulation, which may have increased the comparison between both hands and the difference in embodiment scores. This may also be due to people focusing more on the objects than on their representation, and not being disturbed by the offset which was never big enough to be distracting. We also compared embodiment scores of the two experiments using a Student's t-test. For all conditions, the agency component score from the RL questionnaire was higher in the first experiment than in the second ($p < 0.01$ for G - R and R - G, and $p < 0.05$ for R - \emptyset). People therefore felt a lower sense of agency using the PRISM technique than using the Go-Go technique. The other components scores were similar in both experiments.

As expected, we could not find a significant impact of dual representations on performance. Contrary to papers showing that additional visual information can impact

performance [Tran et al. 2017], in our study dual representations were neither beneficial nor detrimental to the task. It therefore seems possible to use dual representations in such anisomorphic manipulation tasks.

4.6.2 User Preference and Recommendations

The two experiments showed that people globally preferred having a single representation over a dual representation for manipulation. Still, results showed a good acceptance of all representations, dual or single. The questions on user experience had relatively high scores, demonstrating that people liked the different representations and found the interaction easy and clear with them. However, while the general preference was for displaying only the interactive representation, some people found dual representations useful. We hypothesise that individual differences might exist regarding the perception of such a dual representation. One potential explanation could be related to people’s ability to estimate their real body position or whether they are task-oriented. Depending on users’ preferences, they could choose the representation that better suits them.

The results from both experiments give us some insight on how to choose the best virtual representation during 3D anisomorphic manipulation. In general, we suggest to use a single realistic arm as the interactive representation, and to let users the possibility to activate a ghost co-located arm. However, when using a technique in the peripersonal space with small offsets, only keeping a single realistic interactive representation seems sufficient and preferred.

4.6.3 Measuring Embodiment

One of the challenges that we faced in both experiments was how to measure embodiment. While the most common method is the use of subjective questionnaires, it has several limitations as it relies on the participants’ understanding of the questions. Moreover, existing questionnaires have not been designed to assess dual representations. To cope with these limitations, we added specific questions to address dual representations. Furthermore, we considered it a good opportunity to use two questionnaires [Roth and Latoschik 2020; Peck and Gonzalez-Franco 2021], namely PGF and RL, which could be more sensitive to different aspects of embodiment in such a situation. The two questionnaires have different components, but still some comparisons could be made. The RL Ownership and Agency scores were high, and the Change scores low, while the PGF

questionnaire scores all tended to be below average.

The RL Ownership and Agency questions are commonly used in the literature and tended to be high in all conditions, while the Change component questions were found irrelevant by the participants. They reported that they had difficulties answering the questions, suggesting that this component may be used in experiments investigating morphological differences, but probably not in experiments with calibrated avatars. For the PGF questionnaires, all components scores tended to be below average, as some questions (e.g. about tactile sensations) not adapted to the experiment seemed to have lowered global scores and added noise to the results. The questions in this questionnaire are more varied, suggesting a better adaptability to experiments with rich sensory stimulation, as there are questions asking specifically about it.

Overall, the two questionnaires provided different and complementary results. More questionnaires could be designed, as VR setups and experiments are various, and having only one standardised measure of embodiment seems like a difficult goal [Skarbez et al. 2021a].

4.6.4 Limitations

Our experiments were designed to study two common types of motion alteration, either increasing or decreasing motion. However, other types of distortion could be influenced by the representation. For instance, another type of common distortion is collision handling. Dual representations of the virtual hand have been studied for fine manipulation involving collision handling [Canales et al. 2019], where a dual representation provided a good trade-off between performance and preference. It would be interesting to explore the use of dual representations when a collision happens after a larger arm movement, and not only finger movements. While not studied here, dual representations could be appropriate as collisions can create huge offsets between the virtual and the real hand.

Moreover, we decided to display the co-located representation as soon as there was a gain applied. It would also be possible to display the co-located representation only if the offset is greater than a certain threshold. It would avoid having an additional information for precise manipulation like PRISM, when the offset is not disturbing for users, and only display the real hand when users can notice the mismatch and feel a loss of control.

4.7 Conclusion

In this chapter, we investigated the potential use of dual representations during anisomorphic manipulation, to see whether it could ensure both embodiment and performance. We used two different manipulation techniques, namely the Go-Go technique which amplifies motion and the PRISM techniques which decreases motion. With both methods, participants managed to feel a sense of embodiment towards a dual representation. Additionally, no impact was found on performance, which shows that such representations could be used in VR applications. While interacting seemed more important than showing exact movements for agency during out-of-reach manipulation, people felt more in control of the realistic arm during close manipulation. Overall participants preferred having a single representation, but still some people reported the benefit of having a representation showing their real movements to understand the distortion.

The importance of investigating such types of feedback during interaction is crucial, as we do not know yet the optimal visual feedback for each type of technique that would ensure both performance and embodiment. While this study investigated a specific feedback in the context of anisomorphic manipulation, there are already several studies on avatars and manipulation, detailed in Section 1.3 and Section 1.4. Based on the analysis of these studies, we will propose in the next chapter the theoretical concept of “avatar-friendly techniques”, i.e. techniques that take the avatar into account.

Appendix: results of all embodiment questions from the two experiments

Table 4.3 – Summary of all embodiment questions for the first experiment with the Go-Go technique. This table reports the median and interquartile range for each question.

ID	Median[Q1;Q3]		
	R - Ø	R - G	G - R
RL			
wasMyBody	5[3; 6]	4.5[3; 6]	5[3; 6]
bodyParts	5[3; 6]	5[3; 6]	5.5[3.75; 6]
human	5[4; 6]	4[3; 6]	5[3; 6]
belonged	5[3.75; 6]	5[3; 6]	5[3.75; 6]
myMovements	6[5; 6]	5.5[4.75; 6]	5[5; 6]
controlling	6[6; 7]	6[6; 7]	6[6; 7]
causing	7[6; 7]	6.5[6; 7]	7[6; 7]
inSync	6[6; 7]	6[6; 7]	6[6; 6.25]
form	2[1; 5]	2[1.75; 3.5]	3[1.75; 5]
weight	2[1; 2]	2[1; 2]	2[1; 2]
height	2[1; 4]	2[1; 4.25]	2[1; 4]
width	2[1; 2.5]	2[1; 3.25]	2[1; 3]
PGF			
outOfBody	2[1; 3]	2[1; 3]	2[2; 3]
drifting	3.5[1.75; 4.25]	2[1; 3.25]	3[1.75; 3.25]
influencing	3[1.75; 5]	3[1.75; 5]	2.5[1; 4.25]
avatarBody	2[1; 5]	2[1; 4.25]	2[1; 3.25]
posture	2[1; 4.25]	2[1; 3.25]	2[1.75; 3.25]
clothes	2[1; 3.25]	1.5[1; 3.25]	2[1; 3.25]
armLonger	4.5[2; 5.25]	2.5[1.75; 5.25]	3[1; 5]
realisticSensation	5[2; 6]	5[2.75; 6]	3[1; 5]
affected	2[1; 4]	2[1.75; 5]	2[1.75; 4]
wasMyBody	5[3; 6]	4.5[3; 6]	5[3; 6]
resembled	2[1; 4]	3[1; 4.25]	2[2; 4]
located	6[4.5; 6]	6[5; 6]	5[5; 6]
control	6[5.75; 6] ¹	5[4; 6] ²	5.5[5; 6] ^{1,2}
touchLocated	2[1; 3.25]	2[1; 4]	2[1; 4]
touchCaused	2[1; 4]	2[1; 3.25]	2[1; 3]
touching	2[1; 3.25]	2[1; 3]	2[1; 3]

Conditions sharing a superscript were not significantly different (Wilcoxon signed-rank test $\alpha = .05$)

Table 4.4 – Summary of all embodiment questions for the second experiment with the PRISM technique. This table reports the median and interquartile range for each question.

ID	Median[Q1;Q3]			
	R - Ø	R - G	G - R	Ø - R
RL				
wasMyBody	5[3; 6] ^{1,2}	3.5[2; 5.25] ^{1,2}	3[2; 5] ¹	5[3; 6] ²
bodyParts	5[3; 6]	4[2.75; 6]	4.5[2.75; 5.25]	5[3; 6]
human	5[4; 6]	5[2.75; 6]	5[3; 6]	4[3; 6]
belonged	5[2.75; 6]	4.5[3; 6]	4[2.75; 6]	4.5[3; 6]
myMovements	5[3; 6]	5[3; 6]	5[3; 6]	4.5[3; 6]
controlling	6[4.75; 7]	6[5; 6]	5.5[5; 6]	5[4; 7]
causing	6[5; 7]	6.5[4.75; 7]	6[5; 6.25]	6[5; 7]
inSync	5[4; 6]	4.5[3; 6]	5[4; 6]	4[3.75; 6]
form	2[1; 5]	2.5[1; 4]	2[1; 4]	2[1; 4]
weight	1[1; 4]	1.5[1; 3.25]	1[1; 3.25]	1[1; 3.25]
height	1[1; 4]	1[1; 4]	1[1; 4]	1[1; 2.25]
width	1[1; 2.5]	1[1; 2]	1[1; 3]	1[1; 2.25]
PGF				
outOfBody	2[1; 5]	2[1; 3]	2[1; 4]	2.5[1; 5]
drifting	3.5[1.75; 5]	3[2; 4]	2.5[2; 4]	2[1; 4]
influencing	2.5[2; 4]	3[2; 5]	3[1.75; 4.25]	3.5[2; 5]
avatarBody	3[1; 5]	3[2; 4.25]	2[1; 4]	2[1; 4.25]
posture	2.5[2; 4]	2[2; 3]	2[2; 3]	2[1.75; 4.25]
clothes	1.5[1; 5]	1[1; 3]	2[1; 5]	1.5[1; 3.25]
hadChanged	1[1; 3.25]	1[1; 2.25]	2[1; 3]	1[1; 3]
realisticSensation	4.5[3; 5.25]	3[2; 5]	3[2; 5.25]	3.5[2; 5]
affected	4.5[2.75; 6] ¹	3[2; 5] ²	2.5[1; 5] ^{1,2}	5[2; 5] ^{1,2}
wasMyBody	5[3; 6] ^{1,2}	3.5[2; 5.25] ^{1,2}	3[2; 5] ¹	5[3; 6] ²
resembled	3[1; 5]	3[2; 4]	2[1; 4.25]	3[1.75; 5]
located	6[5; 6.25] ¹	4.5[3; 6] ²	4.5[3; 6] ²	5[4.75; 6] ^{1,2}
control	5[3; 6]	4.5[2.75; 5.25]	5[2.75; 6]	5[3; 5.25]
touchLocated	2.5[2; 5]	3[2; 4.25]	2[1.75; 3.5]	2.5[1; 3.25]
touchCaused	3[1; 5]	2[2; 4]	2[1.75; 3.25]	2[1; 4]
touching	3[2; 5]	3[2; 3.25]	3[2; 4]	2.5[1; 5]

Conditions sharing a superscript were not significantly different (Wilcoxon signed-rank test with $\alpha = .05$)

*“And now I’ve come to a realisation that I should create
the person to be in this life”*

Little Simz

DESIGNING AVATAR-FRIENDLY TECHNIQUES: PRACTICAL GUIDELINES

Abstract: This chapter was born out of an analysis of the state of the art on avatars and manipulation. As the related work showed (see Chapter 1), the literature on avatars and manipulation techniques is more extensive than for other interaction tasks. This chapter therefore proposes a set of fourteen guidelines to help VR developers creating manipulation techniques compatible with avatars, which we call avatar-friendly techniques. It also suggests several topics that could be investigated further regarding manipulation techniques and avatars.

5.1 Introduction

VR stakeholders usually design applications based on their instinct, or empirical experience, because of a lack of simple design advice, in the form of guidelines or claims for example. However, proposing and validating design guidelines for VR is already a challenge in itself [Wingrave and LaViola 2010]. There are too many factors impacting interaction, and too many individual differences, that make generalization from experiments very challenging. A set of guidelines for designing VR applications has been proposed by Gabbard [1998], already talking about user representation. For instance, these guidelines recommend to use an efficient embodiment (i.e. provide enough sensory information) and to let users control their appearance in the VE. But, these guidelines are general and not precise enough to design manipulation techniques. Guidelines for designing 3D manipulation techniques have also been proposed by Bowman et al. [2004], however, they do not consider user representation. Other guidelines, heuristics and claims [Sutcliffe and Gault 2004; Tanriverdi and Jacob 2001], more or less general, have been proposed since, but the avatar is usually forgotten. Guidelines specific to manipulation, considering the avatar, would help VR developers and encourage the use of avatars. We propose in this

chapter design guidelines, justified by existing literature, that can be used in early stages of a design pipeline. These guidelines are focused on design choices for manipulation techniques involving avatars, therefore we refer the reader to the guidelines of Gabbard [1998] concerning the remaining of the VR application pipeline (e.g. to restrict latency). Our guidelines are principally aimed towards helping designers to elicit embodiment during manipulation tasks, while also providing insights when a trade-off between embodiment and performance is required. We call this type of techniques “Avatar-Friendly techniques”.

Avatar-Friendly Techniques

Techniques which take the user’s avatar into account in the design process to preserve both user performance and sense of embodiment

The guidelines (see in Table 5.1) are classified into three parts: input devices (ID), control and mapping (CM) and feedback (FB).

5.2 Guidelines

5.2.1 Input Devices

ID1: For specific applications or training, use an input device adapted to the task. *For applications training the user on the use of a specific tool, use an adapted device resembling the real tool. Place the 3D model of the device in the avatar’s hand (see guideline FB5).* Using an adequate device for a task yields better performance [Pham and Stuerzlinger 2019]. This is essential for example when learning technical gestures, but otherwise generic controllers can be used.

ID2: Prioritise full-hand tracking when possible. *Use hand tracking technologies (Leap Motion, gloves) instead of controllers when the tracking works well. In case of tracking issues, consider the use of 6-DoF controllers, especially controllers with capacitive sensors for the fingers.* Using gestures and direct manipulation is preferred to ensure embodiment, realism, enjoyment, but only as long as the tracking is sufficient [Lin et al. 2019; Moehring and Froehlich 2011]. Six-DoF controllers still yield good levels of embodiment in most experiments.

Table 5.1 – Table recapitulating the proposed guidelines and the corresponding sections to justify these guidelines.

Input Devices		
ID1	For specific applications or training, use an input device adapted to the task	Section 1.4.1.1
ID2	Prioritise full-hand tracking when possible	Section 1.4.1.3
Control		
CM1	For wide and fast motions, do not apply constraints	Section 1.4.2.1
CM2	For wide and fast motions, choose a CD gain equal to 1	Section 1.4.2.2
CM3	For small motion and precise manipulation, provide assistance to the user’s movements	Section 1.4.2.4
CM4	For precise manipulation, handle collisions	Section 1.4.2.4
CM5	Progressively increase the distortion gain to make it more acceptable	Section 1.4.2.2
Feedback		
FB1	Provide a well-calibrated avatar	Section 1.3.1.1
FB2	Use first-person perspective	Section 1.4.3.2
FB3	Use slightly transparent hands to prevent occlusions	Sections 1.3.1.2 and 1.4.3.1
FB4	Preserve body continuity as much as possible	Section 1.4.2.3
FB5	Maximize multisensory coherency	Section 1.3.3
FB6	Provide haptic feedback	Section 1.4.3.3
FB7	Use realistic avatars when using distorted motion	Section 1.3.2

5.2.2 Control and Mapping

CM1: For wide and fast motions, do not apply constraints. *When wide and fast movements are done by the user, do not apply constraints (such as avoiding collisions or maintaining a hand pose on an object).* Constraints might create a noticeable mismatch, decreasing the sense of self-location and potentially the sense of agency [Pritchard et al. 2016; Kokkinara et al. 2015].

CM2: For wide and fast motions, choose a CD gain equal to 1. *For wide motion, the best is to keep a gain equal to 1.* A gain lower than 1 could be perceived as latency. A higher gain can quickly create huge offsets between the real hand and the virtual hand, affecting the sense of embodiment [Kokkinara et al. 2015].

CM3: For small motion and precise manipulation, provide assistance to the user’s movements. *Use CD gains lower than 1 to precisely approach an object and/or automatic realistic poses to assist the user in their precise movements.* It is possible to use

subtle modifications of the motion without disturbing the sense of embodiment [Debarba et al. 2018]. This must be used as assistance to provide a visually realistic hand pose to the user during manipulation.

CM4: For precise manipulation, handle collisions. *Constrain the avatar’s hand and fingers outside of virtual objects during manipulation.* Users are more sensitive to collisions than a small mismatch between the position of their virtual hand that of their real one. Therefore, they prefer seeing their virtual hand outside of objects [Canales et al. 2019].

CM5: Progressively increase the distortion gain to make it more acceptable. *The CD gain does not have to be constant, it can evolve during the application. Decrease it slowly to help precise manipulation. Apply a gain to avoid tiring motion, and then set it back to 1.* It was found that distorted motions are better accepted when the distortion is gradually introduced [Porssut et al. 2019; Feuchtner and Müller 2018]. In this case, the sense of embodiment is less impacted.

5.2.3 Feedback

FB1: Provide a well-calibrated avatar. *The avatar’s body measurements (height, general scale, arm length) must match those of the user.* Eye height is important to estimate object size [Leyrer et al. 2011]. Having a personalised hand size was found better for manipulating objects and estimating their size [Jung et al. 2018; Wang et al. 1997].

FB2: Use first-person perspective. *The viewpoint should be co-located with that of the avatar.* First-person perspective is better both for accuracy in manipulation tasks and for the sense of ownership [Gorisse et al. 2017]. This was already recommended by Gabbard to increase the sense of presence [Gabbard 1998].

FB3: Use slightly transparent hands to prevent occlusions. *Make the hand subtly transparent to avoid occlusions and still provide depth cues. It can become transparent when close to an object.* Gabbard already proposed this guideline for selection (see guideline Select7 [Gabbard 1998]). Here we want to highlight that a slightly transparent hand, additionally of being beneficial for performance [Van Veldhuizen and Yang 2021], can also still elicit a sense of agency [Buchmann et al. 2005] and ownership [Martini et al. 2015],

which we confirmed in our study in Chapter 4 with the ghost representation eliciting a good sense of embodiment, especially with the Go-Go technique.

FB4: Preserve body continuity as much as possible. *If anisomorphic motion is used for out-of-reach manipulation (Go-Go technique), use feedback such as a long arm illusion or a robotic arm, but do not break body continuity. Avoid a too high offset that would make the arm too long.* Breaking body continuity during interaction can result in a loss of embodiment [Seinfeld and Müller 2020]. However, if the chosen feedback is a long arm, the embodiment can break when the arm reaches twice the length of the normal arm [Kilteni et al. 2012b]. In this case, other types of feedback could be used, like a “ghost” arm [Yang and Kim 2002] that manipulates the remote object instead of the real arm (see Chapter 4). Raycasting can also be a good alternative since it is more efficient, albeit less intuitive [Poupyrev et al. 1998].

FB5: Maximize multisensory coherency. *If a controller is used, display its 3D model into the avatar’s hand.* It is if the real hand pose is similar to the avatar’s hand pose. It also provides coherency between visual and passive haptic feedback [Insko 2001]. If various virtual tools are used in the application, new input devices have been invented to propose a passive haptic feedback adapted to the virtual tool [Zenner and Krüger 2017].

FB6: Provide haptic feedback. *Use devices that provide haptic feedback during manipulation.* Haptic feedback can increase the sense of embodiment [Fröhner et al. 2019]. It can also help to improve performance when hand tracking is used [Moehring and Froehlich 2011].

FB7: Use realistic avatars when using distorted motion. *Use realistic avatars to make distorted motion less noticeable by the user. One condition for this is to have good hand tracking.* They have several advantages as they make remapped movements less noticeable [Ogawa et al. 2020a] and increase the sense of ownership [Waltemate et al. 2018]. In Chapter 4, we also showed that people preferred to interact with a realistic arm rather than a ghost arm during distorted manipulation. However, realistic avatars increase users’ expectations in terms of control [Argelaguet et al. 2016], therefore they should mostly be used when the tracking works well.

5.3 Future Research Topics

The current state of the art lets us identify several guidelines for designing manipulation techniques. However, there is such a high variety of input or output devices, manipulation techniques and possible virtual representations that our knowledge remains partial. More studies are needed to precise the guidelines, and maybe make them evolve as VR material evolves. This section presents the current gaps in the literature on manipulation techniques and avatars and proposes a number of research topics that should be explored in the future. Most of these research topics arise from the fact that the design of manipulation techniques rarely takes the avatar into account in the design process. This completes the lines of research on user representation proposed by Seinfeld et al. [2020a].

Study perception of motion alterations using different user representations.

Ogawa et al. [2020a] compared the detection thresholds for a spheric cursor and a realistic hand, and found that distorted motion was less noticeable with a realistic hand. More of this kind of studies need to be done to investigate the role of avatars on the detection of distorted motion. It is necessary to understand how to safely modify motion without the user noticing it, or on the contrary to make the alteration more understandable to better accept it (e.g. by displaying a ghost hand showing real movements, as we proposed in Chapter 4). In addition to detection thresholds, motion alterations can influence how users' perceive the task. For example, several works have shown that changes in the CD gain could elicit illusions of weight when lifting virtual objects [Jauregui et al. 2014].

Study different possibilities of feedback and mappings of controller-based input when an avatar is involved.

The perceived sense of embodiment towards the virtual representation highly depends on the mapping and feedback used, based on the information provided by the input device. While there are several studies on hand tracking, there is a lack of investigation on the visual feedback of controller-based input [Lougiakis et al. 2020]. Different mappings for a chosen input device should also be tested.

Compare different input devices to control the avatar during manipulation.

There is an increasing number of controllers proposed that should be compared with one another. For one user representation, several devices can be used to control it [Alzayat

et al. 2019]. The type of input device was found to both affect interaction efficiency and embodiment [Lin et al. 2019]. It would be interesting to compare controllers allowing fingers movement (e.g. Valve Index controllers) to controllers that need to be grabbed (e.g. Vive controllers).

Propose new techniques to separate axes during manipulation while maintaining embodiment.

Constraining manipulation is sometimes needed for the sake of accuracy. For example, the user might want to move an object on a plane, or on an axis. Inspired by 3D desktop interfaces using widgets, similar techniques have been invented for immersive VE [Mendes et al. 2016]. If the user interacts with these widgets via an avatar, additional occlusions and clutching problems can appear. If the avatar does not correctly hold the widget, the feedback can seem unrealistic and disturb embodiment. If the movement is only constrained on a certain axis, users might feel a loss of agency, so it does not seem like a good solution either. It could be interesting to imagine new techniques to manipulate objects independently on different axes without affecting embodiment.

Compare different visual feedback for common techniques.

Different visual feedback can be provided for one chosen technique. For unrealistic interaction, it may be better to provide virtual tools that suggest the use of the technique. For example, putting a laser pointer in the avatar’s hand to use raycasting. In some cases, the avatar can be adapted to the technique (long arm for the Go-Go), but this modifies the avatar appearance and may impact more the sense of embodiment. The impact of visual feedback has been investigated for the Go-Go technique [Feuchtner and Müller 2017], and we have proposed in Chapter 4 a first study exploring the use of dual representations with anisomorphic techniques. Yet, there is a need for more similar studies testing different feedback and their impact on performance and embodiment. Another solution could be to decouple the avatar from the tool used for manipulation. When using anisomorphic manipulation, the transformations could be applied only on the tool, not the avatar. This type of feedback would not affect the avatar itself, thus potentially preserving embodiment.

Study the influence of visual feedback during grasping (collisions, hand poses) on embodiment, especially on the sense of agency.

Nowadays, frameworks (e.g. SteamVR) make it easy to define hand poses for object ma-

nipulation, to have a more realistic visual feedback. Users can be guided to defined poses with subtle assistance, with no impact on embodiment [Porssut et al. 2019]. They are biased to self-attribute assisted movements [Debarba et al. 2018]. However, overly simplistic mappings during grasping might make the user feel less in control. New solutions start to be proposed to automatically compute hand poses in real time [Tian et al. 2019] that could potentially improve embodiment. The moment users release the hand pose might also be crucial for feeling in control, especially when no haptic feedback is used, yet it has rarely been investigated for the moment [Prachyabrued and Borst 2012a].

Explore the impact of multimodal sensory feedback during manipulation on the sense of embodiment.

While there are studies showing the importance of synchronous multimodal feedback on the sense of embodiment, there is a lack of literature on the importance of haptic and auditory feedback, especially during interaction tasks. Yet, the potential impact of such feedback was found on body perception [Fröhner et al. 2019; Tajadura-Jiménez et al. 2015b]. Manipulating objects offers a source of potential feedback that might increase the sense of embodiment.

5.4 Conclusion

In this chapter, we proposed several guidelines to design techniques compatible with avatars. These guidelines concern input devices, control and feedback. We also proposed several research topics that still need some investigation. We hope that in the future, thanks to deeper research on this topic, we will be able to reach good trade-offs ensuring embodiment and efficient manipulation. Finally, the avatar-friendly concept can be extended to other types of interaction (navigation, system control) to provide vibrant 3D experiences to users, as it will be discussed in the next chapter among other perspectives.

CONCLUSION

The goal of this thesis entitled “Towards Avatar-Based Interaction in Virtual Reality” was to better understand the interrelations between the user, the avatar, and the interaction in VR, in order to have future rich interaction while maintaining a good avatar embodiment. Three research axes (RA) presented in introduction guided this research. In this chapter, the different contributions made are summarised, and some perspectives for future research are presented.

6.1 Contributions

First, it was important to better understand the relation between the user and the avatar to know how virtual embodiment was elicited. While several works focused on external factors, i.e. factors depending on the virtual environment or the avatar, this thesis explored internal factors depending on the user (RA1: Influence of the user’s characteristics on the sense of embodiment). In **Chapter 2**, we presented our first contribution, investigating the potential impact of body awareness and several personality traits (Big Five traits and locus of control) on the sense of embodiment. While there was no apparent effect of the Big Five traits and body awareness, positive correlations were found between sense of embodiment and locus of control. In particular, an internal locus of control seems to be correlated with the sense of agency, while an external locus of control seems to affect the sense of ownership. These results can encourage the community to dig deeper into the influence of internal factors, to better understand individual differences in embodiment scores.

Another factor that had not been investigated deeply was the effect of interacting with the VE. To ensure embodiment while interacting, it is essential to know which techniques are better for virtual embodiment, and how they can affect it. While there was an increasing number of works on the impact of manipulation on embodiment, locomotion techniques had rarely been investigated and their impact on embodiment was unknown

(RA2: Influence of the interaction technique on the sense of embodiment). Moreover, most papers on locomotion did not use avatars, thus not taking their potential impact on locomotion into account (RA3: Influence of the avatar on the interaction). Therefore, we decided to investigate the interrelations between locomotion techniques and avatars. An experiment was conducted, presented in **Chapter 3**, using three different locomotion techniques involving a different level of physical motion: real walking, walking-in-place and head steering. In all conditions, the avatar’s movements were reproducing users’ movements. The user representation was used as a within-subject factor, with two levels: only 3D controllers or a full-body avatar. No significant difference between the locomotion techniques was found for the sense of embodiment, showing that having an avatar reproducing users’ movements may be more important than the technique interaction fidelity. However, participants were particularly disturbed by the legs artifacts caused by inverse kinematics, especially in the walking condition. More investigation on the impact of such artifacts could lead to a deeper understanding of the interrelations between embodiment and locomotion techniques.

In addition to locomotion, another essential task in VR is object manipulation. Several techniques, called anisomorphic techniques, distort users’ motion to facilitate interaction, e.g. to reach remote object or to increase precision. These motion distortions can impact the sense of embodiment. Therefore, in **Chapter 4**, we presented two experiments that investigated the use of dual body representations with amplified motion (using the Go-Go technique) and decreased motion (using the PRISM technique). Dual body representations displayed both distorted and real movements. This first study investigating dual representations in this context showed that it was possible to feel a global sense of embodiment towards such representations (RA2), and that they had no impact on performance (RA3). While interacting seemed more important than showing exact movements for agency during out-of-reach manipulation, people felt more in control of the realistic arm during close manipulation. We also found that people globally preferred having a single representation, but opinions diverge especially for the Go-Go technique.

As we mentioned in the related work, the literature on manipulation techniques and avatars is more extensive than on other types of techniques. We analysed previous work on this topic to propose fourteen guidelines, presented in **Chapter 5**, to help VR developers to design avatar-friendly manipulation techniques, i.e. techniques which take avatar embodiment into account during the design process (RA2). The aim is to have techniques that can ensure both performance and virtual embodiment.

6.2 Perspectives

While this thesis is a new step towards having avatar-friendly interaction techniques, our studies have some limitations and there are still many potential leads to explore in order to achieve rich interaction with avatars in VR.

6.2.1 Improve Embodiment Measures

To better understand how the sense of embodiment is elicited, we need to measure it, which is not trivial. For this reason, most studies use subjective questionnaires to measure embodiment. In this thesis, we used such questionnaires in all of our user studies. These questionnaires vary a lot between different experiments, as they highly depend on the experimental conditions. There have been several attempts to create a standardised validated questionnaire [Peck and Gonzalez-Franco 2021; Roth and Latoschik 2020]. Roth et al. [2017; 2020] constructed a novel embodiment questionnaire by relying on factor analysis to propose new leads of standardised questionnaires. Interestingly, their work brought out a novel dimension to evaluate embodiment, named Change (in the perceived body schema), which was not present in the subcomponents proposed by Kilteni et al. [2012a], suggesting that novel dimensions might emerge from the formal construction of novel questionnaires, and which could be more related to interaction. It would be interesting to get more insight on current questionnaires to know when to use them and maybe develop new ones. Having only one standardised questionnaire working for all embodiment experiments seems like a complex task to achieve [Skarbez et al. 2021a], therefore it might be interesting to have numerous small questionnaires adapted to specific cases. Moreover, subjective questionnaires are not always adaptable to every experiment and they still highly rely on participants' understanding of the questions. Studies therefore often add some behavioural responses to add matter to the results. While these responses are often used as an additional measure, and several works show positive correlations between behavioural responses and the sense of embodiment [Yuan and Steed 2010; Zhang and Hommel 2016; Kilteni et al. 2013], it is complicated to know whether they rely on similar neurological processes than virtual embodiment [Ma and Hommel 2013]. The ideal measure would be to have access to users' own mental representations of themselves at any time, but this is not feasible yet. A few cognitive models have been proposed trying to explain the brain processes eliciting the sense of embodiment [Braun et al. 2018]. One main hope for the future is to be able to use brain signals, captured by EEG or MRI, to

find characteristic brain signals when embodying an avatar [Jeunet et al. 2018; Alchalabi et al. 2019].

6.2.2 Offer Customised Parameters to Ensure Embodiment

This thesis highlighted some potential individual factors influencing the sense of embodiment (see Chapter 2). For the first study on this topic, we therefore chose a number of personality questionnaires to explore the potential influence of individual traits. Given the amount of personality questionnaires and cognitive models in the literature, it was 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 be interesting to improve our understanding. For example, other interesting traits that could be studied would be empathy, which was already shown to have an effect on RHI and presence [Asai et al. 2011; Seiryte and Rusconi 2015; Sas and O’Hare 2003], or absorption which was found linked to presence [Kober and Neuper 2013]. Other personal information could be investigated such as cultural differences or racial information. More knowledge will also come from studies using machine learning to enable the identification of different users’ profile, that react differently to VR and embodiment. Some studies already go in the direction of customised experiences, by using reinforcement learning to adapt the experience to each user [Porssut et al. 2021; Llobera et al. 2021]. The ultimate goal would be to be able to predict embodiment levels and have customised experience to optimise embodiment for each user. A pre-experiment questionnaire, with identifies important individual factors, could be proposed so as to predict a user’s level of embodiment prior to the immersion in VR. Being able to create such a questionnaire could prove a valuable tool in the future to adapt the virtual experience to the users in order to maximise their sense of embodiment. This would however also require additional knowledge about which adaptations are more fitted for some categories of users than others.

6.2.3 Study the Importance of Task and User Focus

In VR, an infinity of tasks are possible that could have a different influence on embodiment. In our studies, we always had to choose which tasks to perform, and this choice was often done so as to ensure that people could see the avatar. However, other tasks could be explored.

In Chapter 4, we decided to focus on two types of anisomorphic manipulation techniques. As future work, it could be interesting to explore other tasks creating bigger offsets between the real and the virtual hand. For example, interacting with surfaces that handle collisions could create bigger offsets. We also only used visuomotor tasks in our studies, but it would be possible to replicate these studies with visuotactile stimulation for example, as it necessitates subjects to look at the virtual body. While we wanted to make users interact with the VE and thus using visuomotor stimulation, as it was the focus of this thesis, results might differ a little when using different sensory stimulation.

A recurrent problem in embodiment studies is that participants do not always focus on their avatar, thus making subjective embodiment assessment complicated and unreliable. In our studies, participants sometimes reported that they tended to forget the avatar while doing the task. For example, in the studies of Chapter 4, a few participants reported a difficulty to rank the different virtual representations as they focused on the task and not the avatar during the interaction. Such as in real life, the virtual body is not always necessary to perform a task [Ricca et al. 2020]. Therefore, exploring tasks involving more the actual user’s virtual representation would also be interesting. In the future, it would be better to always know where users have their focus during an experiment, to determine if it has an impact on results, or if having the avatar in the peripheral vision is enough to estimate embodiment. To this end, eye tracking could be an interesting solution to use in embodiment studies to explore the effect of paying attention to the virtual body.

6.2.4 Provide High-Quality Motion Capture

In this thesis we used simple animation techniques (i.e. Inverse Kinematics) to animate avatars during user studies. While Inverse Kinematics is often used in embodiment studies, and quite efficient for animating upper limbs, it showed its limitations mostly in the experiment on locomotion in Chapter 3, in which some participants reported being disturbed by some artifacts in the legs movements. As previous work showed a user preference for high-quality motion capture over Inverse Kinematics [Fribourg et al. 2020a], it could be interesting to run a similar study with higher-quality motion capture systems to evaluate whether differences in terms of embodiment could be influenced by the animation quality in such cases. This was also due to the fact that while we used global calibration to match the avatar’s height to the participant’s, the avatar’s morphology was still different. Several solutions are now starting to appear to easily and precisely calibrate an avatar to the participants morphology [Pujades et al. 2019]. In the future, it will be possible to

have perfectly calibrated avatars and good motion tracking (with external sensors such as cameras, or wearables like inertial sensors).

6.2.5 Extend Design Guidelines to All Interaction Techniques

In Chapter 5, we proposed several guidelines for designing avatar-friendly manipulation techniques. Of course, this concept does not need to be limited to manipulation techniques, but can be extended to all types of interaction techniques. For instance, avatars start to be considered in the design of navigation [Medeiros et al. 2019] or system input techniques [Grubert et al. 2018; Knierim et al. 2018]. When the related work on avatars and other types of techniques is more developed, it will be possible to propose more guidelines. For locomotion techniques, we tried to go in this direction with Chapter 3 by investigating avatar embodiment when using different locomotion techniques. However, more studies are needed to propose guidelines for designing the optimised locomotion technique that ensures embodiment, which ideally also preserves ease of navigation, sense of presence and limits motion sickness. For system input, it would also be interesting to have design guidelines. Most of them would be similar to the ones for manipulation techniques, but other specific guidelines could be added such as using more body-centred widgets, which is an avatar-friendly design already used in most VR applications.

6.2.6 Rethink Evaluation Methods

In Chapter 5, we proposed guidelines for early design phases. As avatars can impact interaction (as detailed in Section 1.3, e.g. influencing users' speed [Tran et al. 2017]), we believe that it is becoming important to also consider evaluating the influence of the avatar throughout the whole design process, as well as to consider novel evaluation methods assessing the compatibility between an avatar and an interaction technique.

Developers and researchers should therefore use embodiment as a novel criterion for assessing the quality of interaction. During iterations of the design process, different types of evaluation are typically performed, where designers use several criteria and heuristics to identify flaws in a current implementation (formative evaluation) or to compare a new final implementation to benchmarks or older implementations (summative evaluation). These criteria are mostly performance-oriented (e.g. accuracy, speed) or user-oriented (e.g. ease of use, predictability). Given the literature now available in regards to the sense of embodiment, we believe that it should progressively become a new criterion for

measuring the quality of interaction, just as breaks in presence were already proposed as new criteria to measure usability [Steed et al. 2005]. In the future, the goal would therefore be to design efficient interaction techniques that do not disrupt embodiment, in which case questions related to the sense of embodiment [González-Franco and Peck 2018; Roth and Latoschik 2020] should be added to formative and summative evaluations to complete evaluations during the iterative design process.

6.2.7 Extend On-Body Interaction

Body-centred interaction is inherently avatar-friendly, as it focuses the interaction on the body, therefore making the virtual body useful and helping the appropriation of it. While it is already common to have body-centered information and widgets in VR applications, it could go further by using the skin as input for example, which has not been deeply explored. Self-touch was already found beneficial for embodiment [Bovet et al. 2018; Hara et al. 2015]. It would be interesting to use more on-skin interaction [Weigel et al. 2015; Meier et al. 2021] and to see its impact on embodiment. Making the avatar central during interaction and interacting directly with the skin, with a congruent visuo-tactile stimulation, could make users regularly focus on the body and could elicit high levels of embodiment.

6.2.8 Embody Multiple Bodies

As highlighted in Chapter 4, multiple bodies have not been investigated a lot in VR studies for the moment, but they might be more explored in the future. It would be interesting to propose a definition and a taxonomy of such multiple representations. Several factors already appear differentiating in such representations: visual appearance, perspective (first-person versus third-person), control (isomorphic versus anisomorphic; synchronised versus alternate), location (co-located bodies or not). Dual representations could represent co-located bodies seen from a first-person perspective, while multiple bodies seen from different perspectives like in the study by Miura et al. [2021] could be called duplicated representations.

Multiple body representations could steer new psychological studies on embodiment, to understand if embodiment switches between several representations or if a “parallel” embodiment emerges, global to all representations [Miura et al. 2021]. In collaborative applications, it would even be possible to create shared embodiment, where multiple users

could share the control, not only of one avatar [Fribourg et al. 2020b] but of multiple avatars. This could offer multiple points of view to the user, common with those of other users, which might be a way to stimulate empathy and collaboration, as it would develop a common perception of the virtual world.

To conclude, we hope this thesis will steer new studies on the interrelations between avatars and interaction and open more questions on this topic, to invent incredible avatar-friendly interaction techniques.

AUTHOR'S LIST OF PUBLICATIONS

Journal

- Dewez, D., Hoyet, L., Lécuyer, A. & Argelaguet, F. (2021). Do You Need Another Hand? Investigating Dual Body Representations During Anisomorphic 3D Manipulation. *Accepted in IEEE Transactions on Visualization and Computer Graphics, IEEE VR 2022 Special Issue*

International Conferences

- Dewez, D., Fribourg, R., Argelaguet, F., Hoyet, L., Mestre, D., Slater, M., & Lécuyer, A. (2019, October). Influence of Personality Traits and Body Awareness on the Sense of Embodiment in Virtual Reality. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 123-134). IEEE.
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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*

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RÉSUMÉ LONG EN FRANÇAIS

Cette thèse intitulée “Interaction Basée Avatar en Réalité Virtuelle” étudie les interrelations entre les avatars et l’interaction en réalité virtuelle (RV). L’objectif est de mieux comprendre comment différentes techniques d’interaction peuvent avoir un impact sur la perception de l’avatar, ainsi que la façon dont le choix d’un avatar peut affecter l’interaction. En particulier, nous nous intéressons à la façon dont ces interrelations peuvent affecter le sentiment d’incarnation. Les contributions de cette thèse aideront les développeurs à concevoir des techniques d’interaction compatibles avec des avatars réalistes au corps entier.

Cette thèse tente de répondre à trois axes de recherche :

- RA1: l’influence des caractéristiques de l’utilisateur sur le sentiment d’incarnation
- RA2: l’influence de la technique d’interaction sur le sentiment d’incarnation
- RA3: l’influence de l’avatar sur l’interaction

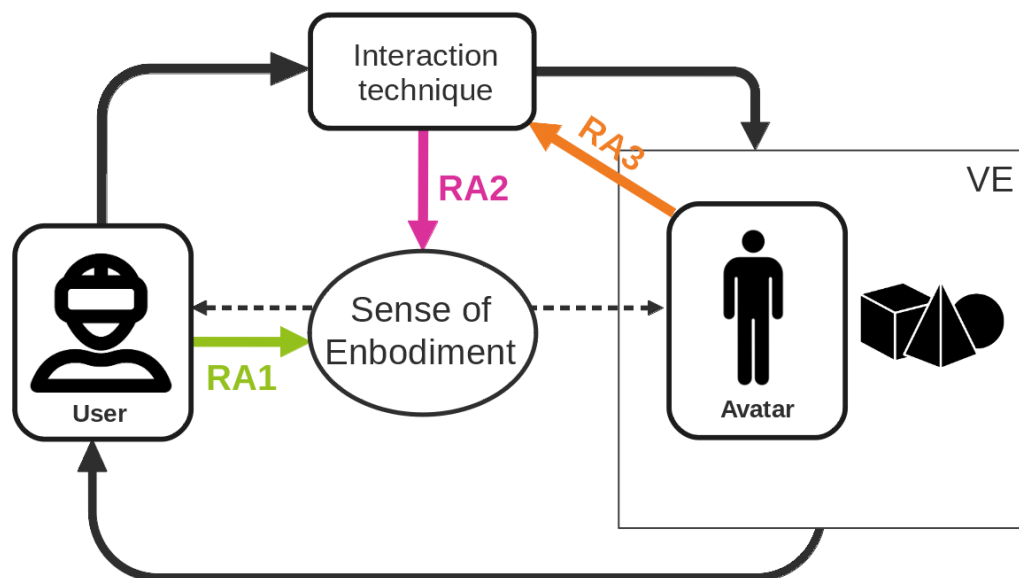


Figure 6.1 – Illustration des différents axes de recherche, reliant l’utilisateur, l’interaction, l’avatar et le sentiment d’incarnation (SoE).

Contexte

La réalité virtuelle (RV) désigne une réalité “virtuelle”, c’est-à-dire “créée par la technologie informatique et semblant exister mais n’existant pas dans le monde physique”. Plusieurs définitions de la RV ont été proposées. Voici une définition technique proposée en 2003.

Définition technique de la Réalité Virtuelle [Arnaldi et al. 2003]

La réalité virtuelle est un domaine scientifique et technique exploitant l’informatique et des interfaces comportementales en vue de simuler dans un monde virtuel le comportement d’entités 3D, qui sont en interaction en temps réel entre elles et avec un ou des utilisateurs en immersion pseudo-naturelle par l’intermédiaire de canaux sensori-moteurs.

La RV immerge les utilisateurs dans un tout nouveau monde, un monde virtuel. Dans cette thèse, nous nous concentrerons sur l’immersion de l’utilisateur par visio-casques (ou HMD). Avec ces casques, l’utilisateur ne voit plus son corps et peut donc être représenté à la place par un avatar, c’est-à-dire un corps virtuel via lequel il peut interagir. L’utilisateur peut ressentir un sentiment d’incarnation [Kilteni et al. 2012a], c’est-à-dire avoir l’impression que l’avatar est son vrai corps.

Interaction en réalité virtuelle

Dans le monde virtuel, il est possible d’agir et d’avoir une influence sur l’environnement virtuel, c’est-à-dire d’interagir avec cet environnement. L’interaction dans un environnement virtuel peut être modélisée à l’aide d’une boucle d’action-perception (voir Figure 6.2).

Les entrées de l’utilisateur peuvent être de différents types, par exemple le mouvement, la voix, le déclenchement d’un bouton. Elles sont transmises à l’application via des périphériques d’entrée, traitées par l’environnement virtuel qui donne un retour grâce à des périphériques de sortie. Le retour d’information peut être cohérent avec l’entrée. Par exemple, un mouvement de l’utilisateur peut être directement imité par l’avatar. Mais parfois, une transformation est appliquée à l’entrée pour obtenir un retour différent, créant ainsi un mouvement déformé. Dans ce cas, on parle d’interaction anisomorphe.

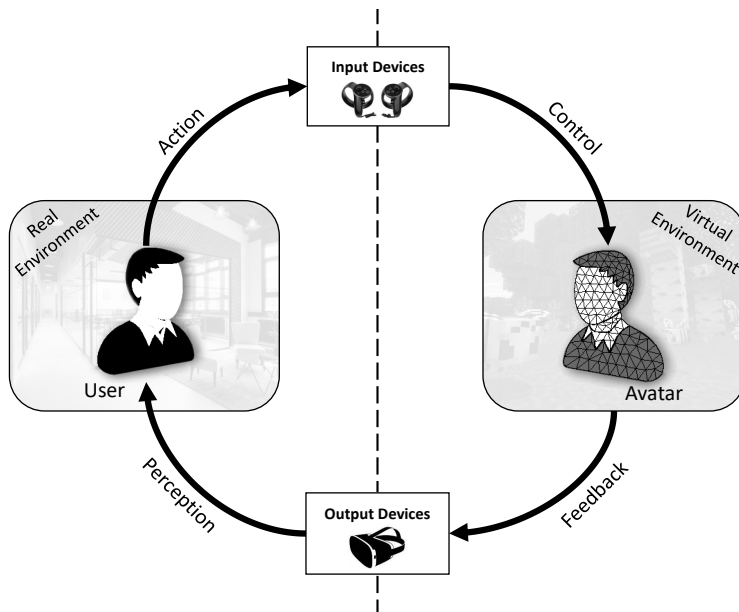


Figure 6.2 – Boucle d’action-perception : l’utilisateur peut contrôler un avatar grâce à des périphériques d’entrée, pour pouvoir interagir avec l’environnement virtuel. En réponse aux actions de l’utilisateur, l’environnement virtuel retourne un feedback qui est perçu par l’utilisateur via les périphériques de sortie.

L’interaction avec l’environnement virtuel peut être classée en quatre catégories [Bowman 1999]: navigation, sélection, manipulation et entrée système. Nous ne nous concentrerons pas sur la saisie système, car la plupart des techniques utilisées pour la saisie système sont similaires à celles utilisées pour la sélection et la manipulation.

La sélection est l’action de choisir l’objet avec lequel l’utilisateur va interagir. Les tâches de manipulation englobent toutes les modifications qui peuvent être effectuées sur l’objet virtuel sélectionné. La sélection et la manipulation peuvent être anisomorphiques. Le mouvement peut être diminué pour offrir un contrôle plus élevé pour un positionnement précis [Frees and Kessler 2005]. Il peut également être amplifié pour atteindre des objets éloignés [Poupyrev et al. 1996].

Les techniques de locomotion permettent aux utilisateurs de se déplacer et de pivoter dans l’environnement virtuel. Plusieurs techniques ont été inventées pour répondre aux contraintes d’espace limité, comme la téléportation ou la marche sur place.

Incarner un Avatar

Dans la RV, les utilisateurs ont la possibilité d'être représentés par un avatar, c'est-à-dire par des parties du corps ou un corps complet qui facilite l'interaction avec d'autres utilisateurs ou avec l'environnement virtuel. Lorsqu'ils utilisent des visiocasques, les utilisateurs ne peuvent plus voir leur corps réel et peuvent avoir l'impression que leur avatar devient leur propre corps. Cette illusion, généralement appelée sentiment d'incarnation, a été définie par Kilteni et al. [2012a]. Cette définition décompose le sentiment d'incarnation en trois sous-composantes : le sentiment de co-localisation, le sentiment d'agentivité et le sentiment d'appropriation. Le sentiment d'appropriation exprime le fait que l'avatar fait partie du corps de l'utilisateur et que c'est à travers lui qu'il reçoit toute stimulation sensorielle. Le sentiment d'agentivité est lié au contrôle de l'avatar. Enfin, le sentiment de co-localisation fait référence à l'emplacement spatial de l'avatar par rapport à la position réelle de l'utilisateur [Blanke and Metzinger 2009].

Le sentiment d'incarnation est souvent mesuré grâce à des questionnaires subjectifs. Les chercheurs ont également essayé d'identifier des mesures objectives qui pourraient être corrélées au sentiment d'incarnation. Comme dans l'illusion de la main en caoutchouc [Ehrsson et al. 2007] (dans laquelle un utilisateur peut avoir l'impression qu'une main en caoutchouc lui appartient après une stimulation tactile), une menace introduite dans le faux corps peut créer une réaction si l'utilisateur se sent incarné [Yuan and Steed 2010; Zhang and Hommel 2016]. D'autres réponses comportementales peuvent être utilisées comme indices supplémentaires d'incarnation, par exemple la fréquence de la voix [Tajadura-Jiménez et al. 2017] ou les mouvements effectués [Kilteni et al. 2013].

L'incarnation est une illusion puissante qui peut avoir des effets cognitifs surprenants. Par exemple, incarner un avatar avec une couleur de peau différente peut réduire les préjugés raciaux implicites [Banakou et al. 2016] ou influencer les performances cognitives des utilisateurs lorsqu'ils incarnent un avatar ressemblant à Einstein [Banakou et al. 2018].

La RV permet le contrôle total d'un grand nombre de facteurs expérimentaux, depuis le protocole de stimulation jusqu'à l'apparence et la morphologie de l'avatar de l'utilisateur, ce qui a donné lieu à un ensemble notable de publications examinant l'impact de ces facteurs sur le sentiment d'incarnation perçu. Ces facteurs peuvent être externes, dépendant de l'environnement virtuel et de l'avatar, ou internes, dépendant de l'utilisateur [Fribourg 2020].

Facteurs externes influençant l'incarnation

Deux méthodes principales existent pour générer un sentiment d'incarnation. La première est la stimulation visuotactile, dans laquelle un objet (pinceau, balle) est utilisé pour toucher le corps réel des utilisateurs en même temps que l'objet virtuel équivalent touche le corps virtuel [Slater et al. 2008]. Le deuxième moyen principal est la stimulation visuomotrice. Pour cela, il faut faire en sorte que l'avatar reproduise les mouvements des utilisateurs [Kokkinara and Slater 2014]. Cette méthode s'est avérée plus efficace que la stimulation visuotactile [Kokkinara and Slater 2014]. La synchronisation spatiale et temporelle est extrêmement importante, notamment pour le sentiment d'agentivité [Jeunet et al. 2018].

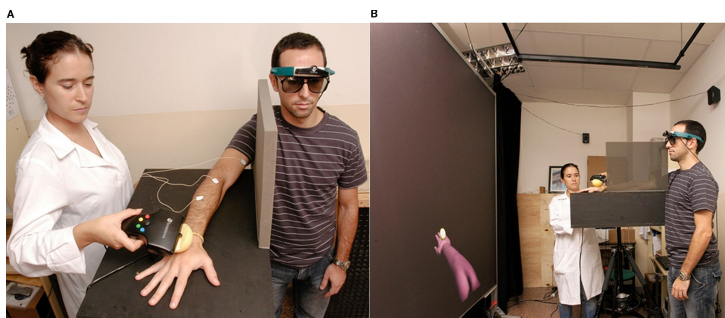


Figure 6.3 – Première expérience en réalité virtuelle utilisant une stimulation visuotactile pour créer un sentiment d'incarnation envers un bras virtuel. Image venant de [Slater et al. 2008].

En plus des facteurs externes concernant le type de stimulation, d'autres facteurs ont également été identifiés comme l'apparence de l'avatar [Maselli and Slater 2013; Waltemate et al. 2018; Gorisse et al. 2019].

Facteurs internes influençant l'incarnation

Certains traits de personnalité pourraient être liés au sentiment d'incarnation. Certains liens ont été trouvés entre la force de l'illusion de la main en caoutchouc et certains traits de personnalité [David et al. 2014; Asai et al. 2011]. Des travaux récents ont commencé à s'intéresser au rôle potentiel des traits de personnalité dans l'incarnation virtuelle. Un exemple est le travail de Jeunet et al. [2018] qui a montré que le sentiment d'agentivité est lié à un locus de contrôle interne, c'est-à-dire que les gens qui se sentent à l'origine des événements de leur vie se sentent également plus en contrôle de leur avatar.

La littérature montre à la fois un intérêt certain et des résultats importants concernant l'influence de la personnalité sur le sentiment d'incarnation des utilisateurs dans le monde physique. Certains travaux plus récents ont également révélé une influence du locus de contrôle, un trait de personnalité, sur le sentiment d'incarnation dans la RV. Ce dernier résultat a mis en évidence le rôle potentiel des différences individuelles dans l'élicitation du sentiment d'incarnation dans la RV et, de cette façon, a soulevé l'intérêt d'explorer plus profondément leur lien possible avec le sentiment d'incarnation dans la RV. Pour cette raison, une partie de cette thèse explorera cette question en étudiant l'effet potentiel des traits de personnalité et de la conscience corporelle sur le sentiment d'incarnation.

Liens entre Interaction et Avatars

Dans la réalité virtuelle, l'avatar sert d'intermédiaire entre le corps réel et l'environnement virtuel. Il montre les actions effectuées par les utilisateurs et peut recevoir visuellement un retour, comme l'utilisateur le ferait dans le monde réel. L'avatar choisi dans une application peut avoir un impact sur la façon dont les utilisateurs interagissent.

Tout d'abord, un avatar affecte la perception qu'ont les utilisateurs de l'environnement virtuel et de leurs capacités. Un avatar permet par exemple de mieux percevoir les distances dans l'environnement virtuel [Mohler et al. 2010]. Il peut également avoir des effets négatifs comme cacher des objets si trop de parties du corps sont affichées. Il a été ainsi montré qu'interagir via un bras peut diminuer la performance comparé à une interaction via seulement une main virtuelle [Tran et al. 2017]. L'avatar permet toutefois parfois d'améliorer la performance, par exemple dans une tâche de tir à l'arc virtuel [Gao et al. 2020]. Cela semble donc dépendre de la tâche.

Inversement, l'interaction peut avoir un impact sur la perception de l'avatar et notamment sur le sentiment d'incarnation. Par exemple, le sentiment d'appropriation est plus élevé en utilisant directement les mains pour interagir plutôt que des manettes [Lin et al. 2019]. Certaines techniques peuvent aussi modifier le contrôle que l'utilisateur a de son avatar, par exemple ralentir les mouvements pour gagner en précision [Frees and Kessler 2005]. Cependant, introduire des décalages entre la main virtuelle et la main réelle de l'utilisateur peut avoir des conséquences sur l'incarnation, notamment sur le sentiment de co-localisation [Pritchard et al. 2016].

Il y a donc en RV différentes études sur le sentiment d'incarnation envers un avatar, ainsi que sur les meilleures manières d'interagir avec l'environnement virtuel, mais peu

d'études liant les deux domaines. Pourtant, il existe des interrelations entre incarnation et interaction qu'il est nécessaire de mieux comprendre. Dans les prochaines sections, nous présentons nos différentes contributions pour mieux comprendre les liens entre avatars et interaction, afin de créer des techniques plus compatibles avec les avatars.

Etude des Différences Individuelles Dans le Sentiment d'Incarnation



Figure 6.4 – De gauche à droite : un exemple de trajectoire à dessiner pendant l'expérience; Une vue de derrière de la scène virtuelle; Un autre personnage virtuel en train de poignarder la main virtuelle du participant à la fin de l'expérience pour mesurer sa réponse à la menace sur son corps virtuel.

Dans le chapitre 2 de cette thèse, nous présentons une expérience utilisateur réalisée avec 123 participants sur l'impact potentiel de la personnalité sur le sentiment d'incarnation. Plusieurs traits ont été étudiés: les traits du "Big Five" [John et al. 1991; Plaisant et al. 2010] (Ouverture à l'expérience, Conscienciosité, Extraversion, Agréabilité, Neuroticisme), le locus de contrôle [Levenson 1981; Loas et al. 1994] et la conscience corporelle [Shields et al. 1989; Dumont 2013]. Un questionnaire subjectif a été utilisé pour mesurer le sentiment d'incarnation. En plus de ce questionnaire, une menace a été introduite à la fin de l'expérience pour observer la réaction de l'utilisateur. Cette méthode est courante dans les études d'incarnation, car la réaction à la menace est généralement positivement corrélée à l'intensité du sentiment d'incarnation [Yuan and Steed 2010].

Nous avons globalement trouvé que le locus de contrôle semblait être lié à deux composantes de l'incarnation. Le sentiment d'appropriation semble être plutôt influencé par un locus dit externe (le fait de penser que ce qui nous arrive est dû à des éléments extérieurs tel que le destin), alors que le sentiment d'agentivité est positivement corrélé par

un locus dit interne (le fait de penser que ce qui nous arrive est dû à nos propres actions). Nous avons également trouvé que la réaction et la perception de la menace étaient positivement corrélés avec le neuroticisme.

Etude de l'Impact des Techniques de Locomotion sur le Sentiment d'Incarnation



Figure 6.5 – Illustration des quatre tâches effectuées par les participants durant notre étude utilisateur, toutes dans la condition avec l'avatar au complet. Les mêmes tâches ont également été réalisées sans avatar. De gauche à droite : Tâche d'entraînement, tâche du couloir, tâche de suivi de chemin et tâche des colonnes.

Dans le chapitre 3, nous nous intéressons à l'impact de l'interaction sur l'incarnation, et plus précisément à l'impact du choix de la technique de locomotion sur le sentiment d'incarnation. Trois techniques ont été étudiées, impliquant chacune un degré différent de mouvements physiques et de similitude avec la marche naturelle : la marche réelle, la marche sur place et le steering (appuyer sur un bouton pour avancer). Chaque participant utilisait une seule technique. Il faisait deux fois l'expérience, une fois représenté par un avatar au corps complet, et une autre fois avec juste une représentation virtuelle des manettes qu'il tenait. L'expérience consistait en différentes tâches montrant différentes parties du corps. Une première tâche permettait à l'utilisateur de voir indirectement son corps en entier en faisant des allers-retours dans un couloir avec des miroirs à chaque extrémité. Dans la deuxième tâche, l'utilisateur devait suivre une croix qui se déplaçait sur une trajectoire. La croix était juste devant lui, le forçant à avoir ses jambes dans son champ de vision. Enfin, la troisième tâche impliquait de se déplacer pour aller ramasser des champignons, dans laquelle l'utilisateur voyait donc surtout ses bras. Il devait également éviter des colonnes pour aller ramasser les champignons.

Nos résultats montrent que le sentiment d'incarnation ne semble pas influencé par la

technique de locomotion. Cela suggère que le fait d’avoir le contrôle de l’avatar (dans toutes les conditions l’avatar faisait les mêmes mouvements que l’utilisateur) semble plus important que la technique de locomotion en elle-même.

Etude de l’Utilisation d’une Représentation Double Pendant de la Manipulation Anisomorphique

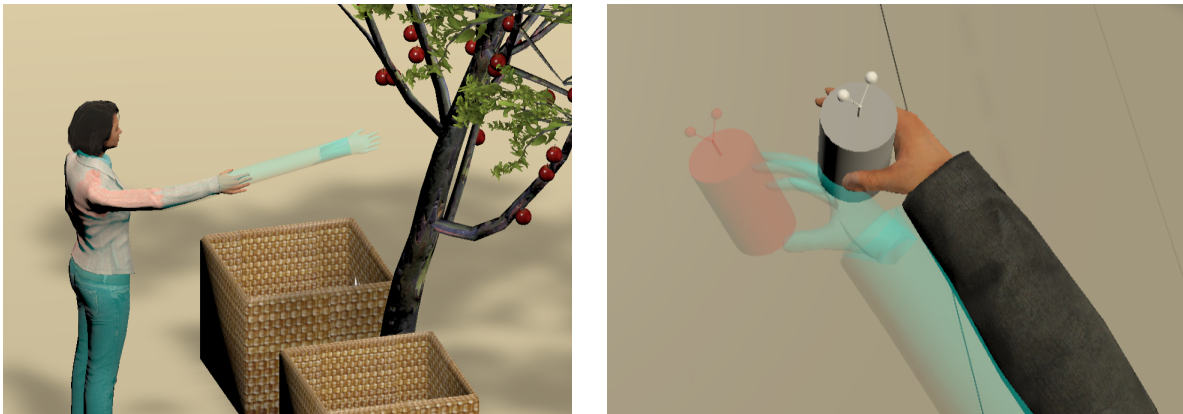


Figure 6.6 – Illustration de deux types de représentations doubles étudiées dans ce chapitre. Sur l’image de gauche, une représentation fantôme permet une manipulation à distance tandis qu’une représentation réaliste co-localisée fournit un retour par rapport à la position réelle de l’utilisateur. Sur l’image de droite, une représentation fantôme fournit un retour par rapport à la position réelle de l’utilisateur tandis qu’une représentation réaliste permet une manipulation précise avec l’environnement grâce à un mouvement ralenti.

Dans le chapitre 4, nous étudions un autre type de technique d’interaction, la manipulation d’objets. Plus précisément, nous nous focalisons sur la manipulation anisomorphique qui modifie les mouvements de l’utilisateur, par exemple pour amplifier les mouvements pour atteindre des objets lointains, ou pour ralentir le mouvement pour gagner en précision. Ce type de techniques peut avoir un impact sur le sentiment d’incarnation, car les mouvements de l’avatar sont différents des mouvements de l’utilisateur. Les sentiments d’agentivité et de co-localisation sont potentiellement les plus impactés, car il y a un décalage entre les mouvements réels et virtuels [Kokkinara and Slater 2014; Pritchard et al. 2016]. Nous avons donc réalisé une étude pour explorer une potentielle solution : l’utilisation d’une représentation double. Une représentation sert à montrer les mouvements déformés aidant à l’interaction, pendant qu’une autre représentation co-localisée

montre les mouvements réels de l'utilisateur. Nous voulions voir l'impact potentiel de ce type de représentation virtuelle sur le sentiment d'incarnation et la performance. Nous avons réalisé deux expériences, l'une avec des mouvements amplifiés (avec la technique Go-Go [Poupyrev et al. 1996]), l'autre avec des mouvements ralentis (avec la technique PRISM [Frees et al. 2007]). Pour chaque expérience, les représentations doubles étaient comparées à des représentations simples avec un seul avatar. Dans chaque condition, les mouvements déformés et réels pouvaient être représentés par: un avatar réaliste, un avatar fantôme transparent ou aucune représentation.

Avec les deux techniques de manipulation, les participants ont réussi à ressentir un sentiment d'incarnation pour les différentes représentations doubles. De plus, aucun impact n'a été constaté sur la performance, ce qui montre que de telles représentations pourraient être utilisées dans des applications de RV. Alors que l'interaction semblait plus importante que la présentation des mouvements réels pour l'agentivité avec la technique Go-Go, les personnes se sentaient plus en contrôle du bras réaliste pendant la manipulation avec PRISM. Dans l'ensemble, les participants ont préféré avoir une représentation simple, mais certains ont tout de même signalé l'avantage d'avoir une représentation montrant leurs mouvements réels pour comprendre la distorsion créée par la technique d'interaction.

Conseils pour le Design de Techniques d'Interaction Compatibles avec l'Avatar

Pour terminer cette thèse, nous proposons dans le chapitre 5 des directives de conception pour créer des techniques de manipulation compatibles avec les avatars. Ces directives sont classées en trois catégories: entrée, contrôle et feedback. Elles sont basées sur une analyse de l'état de l'art actuel sur les techniques de manipulation et les avatars. Nous avons étudié à la fois l'impact des avatars sur la manipulation et l'impact des choix de design sur le sentiment d'incarnation (voir le détail dans le chapitre 1). En plus des directives de design, nous proposons également des pistes de recherche pour la suite, toujours focalisées sur les techniques de manipulation.

Table 6.1 – Tableau récapitulatif des directives de design proposées et les sections correspondantes qui justifient ces directives.

Entrée		
ID1	Pour des applications ou des formations spécifiques, utiliser un périphérique d'entrée adapté à la tâche	Section 1.4.1.1
ID2	Privilégier le suivi des mains lorsque cela est possible	Section 1.4.1.3
Contrôle		
CM1	Pour les mouvements larges et rapides, ne pas appliquer de contraintes aux mouvements	Section 1.4.2.1
CM2	Pour les mouvements larges et rapides, choisir un gain égal à 1	Section 1.4.2.2
CM3	Pour les petits mouvements et les manipulations précises, assister les mouvements de l'utilisateur	Section 1.4.2.4
CM4	Pour les manipulations précises, gérer les collisions	Section 1.4.2.4
CM5	Augmenter progressivement le gain de la distorsion pour la rendre plus acceptable	Section 1.4.2.2
Feedback		
FB1	Bien calibrer l'avatar	Section 1.3.1.1
FB2	Utiliser une vue à la première personne	Section 1.4.3.2
FB3	Utiliser des mains légèrement transparentes pour éviter les occultations	Sections 1.3.1.2 et 1.4.3.1
FB4	Préserver autant que possible la continuité du corps	Section 1.4.2.3
FB5	Maximiser la cohérence multisensorielle	Section 1.3.3
FB6	Fournir du retour haptique	Section 1.4.3.3
FB7	Utiliser des avatars réalistes lors de l'utilisation de mouvements déformés	Section 1.3.2

Conclusion

Les différentes contributions de cette thèse ont pour but d'aider le développement des techniques d'interaction compatibles avec les avatars, c'est-à-dire des techniques qui sont efficaces mais qui permettent aussi de maintenir un bon sentiment d'incarnation envers l'avatar. En étudiant à la fois comment l'incarnation apparaît selon les profils des utilisateurs, comment les différentes techniques d'interaction peuvent aussi influencer cette incarnation, cette thèse s'intéresse autant à l'action qu'à la perception. Dans le futur, il serait intéressant d'approfondir les connaissances sur l'incarnation en réfléchissant à de meilleurs moyens de la mesurer et de la maximiser pour chaque utilisateur. Il serait intéressant aussi d'explorer des nouvelles méthodes d'interaction comme l'interaction sur la peau, et d'étendre les directives de design aux autres techniques d'interaction et pas seulement la manipulation d'objets. A long terme, la possibilité d'avoir des interactions riches via un avatar permettra par exemple aux utilisateurs de tester et d'apprendre de nouvelles compétences en RV.

Titre : Interaction Basée Avatar en Réalité Virtuelle

Mot clés : Avatars, sentiment d'incarnation, interaction, réalité virtuelle

Résumé : La réalité virtuelle permet d'immerger des utilisateurs dans un monde alternatif. Dans ce monde virtuel, ils peuvent se déplacer ou encore interagir avec des objets grâce à leur corps virtuel, aussi appelé avatar, qui leur indique où ils se trouvent et ce qu'ils sont en train de faire. Les utilisateurs peuvent même se sentir incarnés dans cet avatar et ainsi avoir l'impression que c'est leur vrai corps. Cette illusion offre une expérience utilisateur intéressante et peut avoir des conséquences surprenantes comme augmenter les capacités cognitives d'une personne. Cependant, il n'est pas encore clair comment cette illusion est créée. De plus, les techniques actuelles d'interaction sont parfois peu compatibles avec des avatars réalistes,

notamment parce qu'elles déforment parfois les mouvements de l'utilisateur, et donc potentiellement le corps et les mouvements de l'avatar, ce qui peut influencer le sentiment d'incarnation. Cette thèse propose plusieurs études pour mieux comprendre les relations entre utilisateur, avatar et interaction. Elle se concentre sur le sentiment d'incarnation, en étudiant à la fois des facteurs individuels et l'impact de différents feedbacks pendant des tâches d'interaction (locomotion et manipulation d'objets). Des conseils de conception de techniques d'interaction compatibles avec les avatars sont aussi proposés, ainsi que des pistes de recherche pour le futur. Le but à long terme est d'avoir des interactions efficaces qui assurent un haut sentiment d'incarnation.

Title: Towards Avatar-Based Interaction in Virtual Reality

Keywords: Avatars, sense of embodiment, interaction, Virtual Reality

Abstract: Virtual reality enables users to be immersed in an alternative world. In this virtual world, they can move around or interact with objects through their virtual body, also called an avatar, which tells them where they are and what they are doing. Users can even feel a sense of embodiment towards this avatar and have the impression that it is their real body. This illusion offers an interesting user experience and can have surprising consequences such as increasing a person's cognitive abilities. However, it is not clear yet how this illusion is elicited. Furthermore, current interaction techniques are sometimes not compatible with realistic avatars, especially because they

sometimes distort the user's movements, and thus potentially the avatar's movements and body, which can influence embodiment. This thesis proposes several studies to better understand the relationship between user, avatar and interaction. It focuses on the sense of embodiment, investigating both individual factors and the impact of different feedbacks during interaction tasks (locomotion and object manipulation). Design guidelines for avatar-compatible manipulation techniques are also provided based on existing literature, as well as leads for future research. The ultimate goal is to have effective interaction that provides a high sense of embodiment.