International Conference on Artificial Reality and Telexistence
Eurographics Symposium on Virtual Environments (2022)
J.-M. Normand and H. Uchiyama (Editors)

Manipulating the Sense of Embodiment in Virtual Reality: a study of the interactions between the senses of agency, self-location and ownership

Martin Guy[1], Camille Jeunet-Kelway[2], Guillaume Moreau[3] and Jean-Marie Normand[1]

[1] Nantes Université, ENSA Nantes, École Centrale Nantes, CNRS, AAU-CRENAU, UMR 1563, F-44000 Nantes, France
[2] Univ. Bordeaux, CNRS, EPHE, INCIA, UMR5287 F-33000 Bordeaux, France
[3] IMT Atlantique - Lab-STICC UMR 6285, France

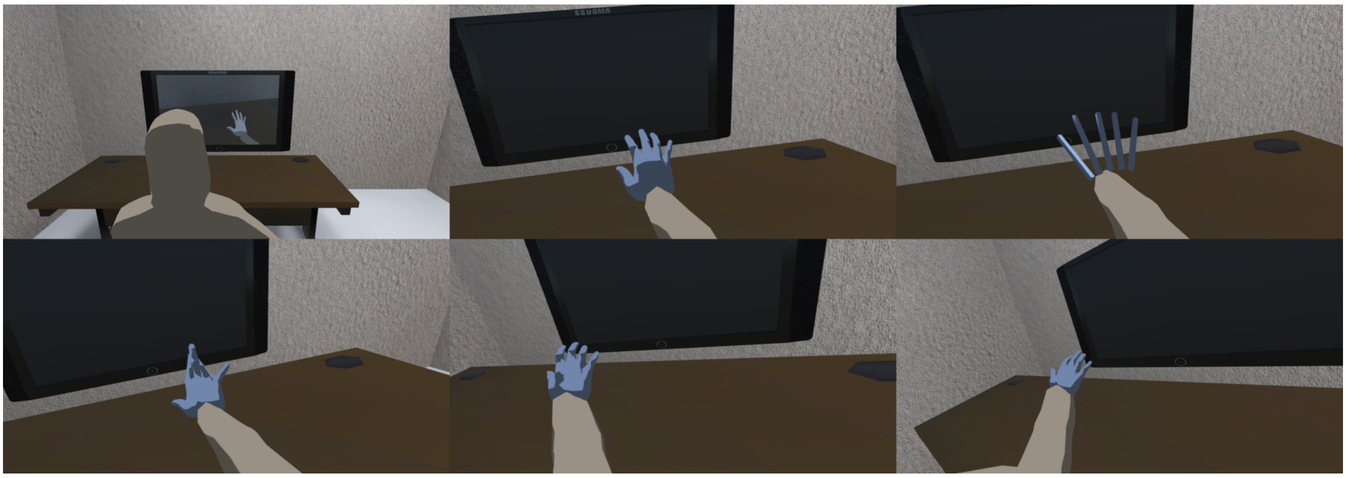

Figure 1: *This experiment assessed the sense of embodiment during right-hand movements with different levels of agency, different levels of virtual hand realism, and different levels of self-location. (Top-left) Overview of the Virtual Environment used in the experiment. The participant's avatar is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

Abstract

In Virtual Reality (VR), the Sense of Embodiment (SoE) corresponds to the feeling of controlling and owning a virtual body, usually referred to as an avatar. The SoE is generally divided into three components: the Sense of Agency (SoA) which characterises the level of control of the user over the avatar, the Sense of Self-Location (SoSL) which is the feeling to be located in the avatar and the Sense of Body-Ownership (SoBO) that represents the attribution of the virtual body to the user. While previous studies showed that the SoE can be manipulated by disturbing either the SoA, the SoBO or the SoSL, the relationships and interactions between these three components still remain unclear. In this paper, we aim at extending the understanding of the SoE and the interactions between its components by 1) experimentally manipulating them in VR via a biased visual feedback, and 2) understanding if each sub-component can be selectively altered or not. To do so, we designed a within-subject experiment where 47 right-handed participants had to perform movements of their right-hand under different experimental conditions impacting the sub-components of embodiment: the SoA was modified by impacting the control of the avatar with visual biased feedback, the SoBO was altered by modifying the realism of the virtual right hand (anthropomorphic cartoon hand or non-anthropomorphic stick "fingers") and the SoSL was controlled via the user's point of view (first or third person). After each trial, participants rated their level of agency, ownership and self-location on a 7-item Likert scale. Results' analysis revealed that the three components could not be selectively altered in this experiment. Nevertheless, these preliminary results pave the way to further studies.

CCS Concepts

• ***Human-centered computing*** → ***Mixed / augmented reality; User studies;***

DOI: 10.2312/egve.20221281

1. Introduction

Virtual Reality (VR) is a growing field, becoming more and more accessible to the public. Virtual bodies (usually referred to as avatars) are increasingly often used in Virtual Environments (VEs), due to the many applications of VR such as entertainment [ASK20], interactive training [BGB*15], scientific visualisation [DMI*18] or virtual therapy [Lin20]. It is thus important to better understand the Sense of Embodiment (SoE): that is "the subjective experience of using and having a body" [BM09]. In the context of VR, hardware and software can "substitute a person's body with a virtual one" [SNB*14] and the SoE is typically characterised by three components (although being a topic of discussion [PGF21]): the Sense of Agency (SoA), the Sense of Self-Location (SoSL) and the Sense of Body-Ownership (SoBO) [KGS12]. The SoA is the feeling of being the cause of our actions. The SoSL is the spatial experience of being inside a body. Finally, the SoBO is the feeling that the virtual body is the source of my sensations (like my real body). Deepening the comprehension of these three components would help better understand the SoE. However, the relationships and interactions between SoA, SOBO and SoSL still remain unclear, especially in a VR context, as many of the existing studies only focus on 1 or 2 components at the same time. In this paper, our aim is to better understand the SoE and the interactions between its components by 1) experimentally manipulating independently the SoA, SoSL and SoBO in VR, and 2) study to what extent each component can be selectively altered. To do so, we designed a within-subject experiment where 47 right-handed participants performed movements of their right-hand under different experimental conditions impacting the components of the SoE (see Figure 1): the SoA was modified by impacting the control of the avatar with a biased visual feedback, the SoSL was controlled via the user's point of view (first-person, third-person in peripersonal space or third-person in extra-personal space) and the SoBO was altered by modifying the realism of the virtual right hand (anthropomorphic cartoon hand or non-anthropomorphic "stick fingers"). After each trial, participants rated their levels of agency, ownership and self-location on a 7-item Likert scale. To the best of our knowledge, this is the first time that SoA, SoSL and SoBO are manipulated in a same VR experiment to study their interactions.

This paper is structured as follows. Section 2 gives an overview of related work on the SoE, SoA, SoBO and SoSL and details how they were previously manipulated. Section 3 presents the experimental protocol and design as well as our research hypotheses. Our results are analysed in Section 4 and discussed in Section 5. Finally, Section 6 concludes this work and presents some future works.

2. Related Work: The Sense of Embodiment in Virtual Reality

Although the Sense of Embodiment is studied in multiple communities [BM09,dV11,Gal00], we focus here on the SoE in the context of VR and present how it can be manipulated in VR experiments. To do so, we study it through the prism of its three components, as defined by Kilteni et al. [KGS12]. Many factors impact the SoE, e.g. the avatar's appearance, the Virtual Environment (VE), and also the user's personality and preferences [Fri20, Dew21]. More precisely regarding the avatar, in addition to its appearance (which mostly relates to the SoBO), the amount of control of the avatar (related to the SoA) and the point of view (linked to the SoSL) play an important role on the SoE.

2.1. The Sense of Agency

The Sense of Agency is defined by statements like *"I am the one in control of my actions"* or *"this is me that opened the door"*. According to Gallagher, it is *"the sense that I am the one who is causing or generating an action"* [Gal00]. Not only does this refer to generating an action, it also considers the outcome from this action, by making a change in the environment. Following the neuroscience community's definition of Blanke and Metzinger [BM09], the SoA refers to the sense of having "global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will". For a review of the SoA, see [BDS*18, Hag17].

The way users interact with the VE and their avatar impacts their level of immersion: having controllers in hands or using hand-tracking will not result in the same experience of embodiment. For instance, having foot-tracking significantly improves the SoSL as well as the SoA [EMFM21].

It has been shown that the SoA can be modulated in VR by means of biased visual feedback, where the outcome of an action does not match the intended action [KIS*15,PGFSV*16,JAAL18]. In [PGFSV*16], the virtual hand of the avatar sometimes moved in the opposite of the intended direction. In [JAAL18], the SoA was manipulated in three different ways: (i) adding temporal lag in the user's movement; (ii) inverting two fingers; or (iii) having one finger moving by itself. All three manipulations altered the SoA.

2.2. The Sense of Self-Location

According to Kilteni et al. [KGS12], self-location *"is a determinate volume in space where one feels to be located"*. In this way, the Sense of Self-Location refers to the spatial experience of being inside a *body*. The avatar can be embodied in a first-person perspective (1PP) [SSSVB10, PWL*14, AHTL16, KBS13], imitating the way one observes the world in everyday life in healthy situations, or in third-person perspective (3PP), simulating an out-of-body experience, and watching the body from an external point of view [LTMB07, SSSVB10, BBOS17, Ehr07]. The SoSL is thus based on the visuospatial perspective (1PP or 3PP). However, it also considers vestibular signals, and tactile inputs. Vestibular signals consist of body information of rotation, translation, and orientation in relation to gravity [BM09]. Patients who experienced out-of-body experiences (feeling to be outside of their body with the visual perspective also coming from outside the body) had vestibular dysfunction [BLSS04]. Finally, tactile inputs are related to the way the brain encodes its surrounding space relatively to the body (personal space – the skin; peripersonal space – everything at grasping range; and extrapersonal space – anything out of reach [KGS12]).

The SoSL can thus be manipulated in VR by (i) changing the point of view from 1PP to 3PP [LTMB07, SSSVB10, BBOS17, Ehr07], or (ii) with synchronous visuo-tactile stimulations. For instance, Normand et al. [NGSS11] embodied participants in avatars with different body volumes than their real body, which resulted in a differently perceived personal space.

2.3. The Sense of Body-Ownership

The Sense of Body-Ownership is defined by statements like *"this is my hand"* or *"I am the one who is having this feeling"* [BDS*18]. This feeling has first been addressed in the Rubber-Hand Illusion (RHI) experiment of Botvinick and Cohen [BC98]. They showed that one can have a feeling of ownership toward a fake rubber hand, after stroking simultaneously with a brush one's real hand and the rubber hand. This experiment was extended to VR with a feeling of ownership toward a virtual hand [IdKH06, YS10], a virtual arm [LTMB07] and a full body [SPMESV09]. For a review of the SoBO, see [BDS*18].

The SoBO has been found to be impacted by the avatar's appearance [PE08, AHTL16], which can vary in shape, colour or height. It has been shown that increasing the avatar's realism improved the SoBO and therefore the SoE [AHTL16, LJ16] (although an uncanny valley effect can exist to a certain extent [Mor12, LLL15]).

2.4. Interaction between the components

As of now, we know that the three components of the SoE (SoA, SoSL and SoBO) are not independent but rather interact with each other. However, the interactions between them remain unclear. While a vast part of the literature investigates existing interrelations between them, there is still some variability in the results. In the previous sections, we reviewed how each component can be manipulated in VR experiments, but these manipulations may impact the other components as well. Indeed, as the visuospatial perspective is related to the SoSL, it was also found to play a role in the SoBO [PKE11]. More precisely, SoBO and SoSL are strongly coupled, and breaking the SoSL reduces the SoBO. However, in their experiment, Maselli and Slater found that the SoBO and the SoSL can be selectively altered, depending on the distance between the user's perspective and the virtual body [MS14].

The link between the SoSL and the SoA is the least explored interaction. Nevertheless, David et al. [DBC*06] claim that the two are independent. While using avatars, this experiment was however not in VR but on a screen-based desktop 3D environment. The SoSL was modified by changing the visuospatial perspective from 1PP to 3PP, and the SoA was either present in an active task (pressing a button to throw a ball) or absent in a passive task (indicating which avatar is throwing a ball).

Finally, there is some discrepancy in the results toward the interaction between the SoA and the SoBO. Some neuroscience studies (not in VR) showed that the two were related [TSBG07] while others (still not in VR) found them to be independent [KE12, TLH10]. There are two models accounting for this interaction: an additive model in which they are both strongly related, and an independent model where the SoBO and the SoA are qualitatively different experiences, with distinct brain networks, as denoted by Tsakiris et al. [TLH10]. In VR experiments, while the visual realism and appearance of the avatar were shown to impact the SoBO [AHTL16, LJ16, CHLL18], its relationship with the SoA is less clear. Indeed, it was sometimes found to also impact the SoA [AHTL16] and sometimes not [LJ16]. The relationship between these two components of the SoE may vary depending on the experimental conditions, as stated by Chen et al. [CHLL18].

To the best of our knowledge, this is the first experiment studying the interaction between the three components at the same time. To summarise, existing results tend to show that the SoA and the SoBO are partly dependent, and that the SoSL may be independent from the SoA while closely related to the SoBO.

3. Material and Methods

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

3.1. Participants

Fifty (50) participants were originally recruited in the experiment. Three participants were removed due to issues during the recording of their data. So, a total of 47 participants (27 men, 20 women, 28.43±11.05 year-old (mean±SD)) took part in the experiment. All participants had normal or corrected-to-normal vision. As the questionnaire was only in french, the population was restricted to french speaking people. Because we asked participants to perform right-hand movements, we also recruited only right-handed persons, as we cannot assess if handedness might impact our dependent variables in this study. The experimental protocol has been approved by the internal review board of Université de Nantes.

3.2. Experimental manipulation of the components of the SoE

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

3.2.1. Agency Manipulation

The SoA is manipulated by means of biased visual feedback (the outcome of an action does not match the intended action). In this experiment, there are two agency conditions:

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

The SoA is manipulated following Jeunet et al. experiment's [JAAL18] in three different ways: (i) adding 1s of temporal lag in the user's movement; (ii) having the thumb moving by itself; or (iii) inverting the 2nd and 4th fingers (see Figure 1). These three manipulations were kept in order to add variety to the experiment and be more representative of tracking issues that could alter the SoA. These manipulations of the SoA are nonetheless not distinguished in the experimental protocol nor in the analysis (as they were found to all have an effect in [JAAL18]).

3.2.2. Self-Location Manipulation

The SoSL is manipulated by changing the visuospatial perspective of the user (either 1PP or 3PP). In this experiment, there are three self-location conditions (see Figure 1):

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

Indeed, as mentioned in Section 2.4, it was shown that the visuospatial perspective has an impact on the SoBO but only in certain conditions [MS14]. In their experiment, Maselli and Slater changed the visual perspective of participants in a VR experiment: either (i) in 1PP with a total overlap of the participant's real body and the virtual body; (ii) in a 3PP shifted around 25cm to the right with the left leg of the participant being near the right leg of the avatar; or (iii) in a 3PP shifted 80cm to the right of the virtual body, so that there is no overlap at all between the participant's real body and the virtual body. The authors observed that the SoSL was altered in both 3PP conditions, but the SoBO was preserved in the 3PP at 25cm compared to the 3PP at 80cm. This is what we wanted to replicate in this experiment, in order to selectively alter each component. However, due to technological constraints, the virtual body could not be 80cm away from the participant since, at that distance, the hand tracking was lost when not looking at the hand. Indeed, when the visuospatial perspective is shifted laterally to the right, the users turn their head to the left to see the virtual body (see Figure 1) while their real hand stays in front of them. In that configuration, the VR headset was unable to perform stable hand-tracking, the real hand of the participant being outside of the range of the HMD's sensors. We experimentally found out that the avatar could be located at a maximum of $\sim$50 cm away from the participant for hand-tracking to work for an average participant. Fortunately, 50cm is at the border of peripersonal space (reported at 45 ± 7cm in [RFML20]).

3.2.3. Body-Ownership Manipulation

In VR, the SoBO can be manipulated with visuo-tactile asynchronous stimulations [BC98] or changing the appearance of the avatar's hand [AHTL16, LJ16, CHLL18]. In this experiment, there are two body-ownership conditions:

- *Anthropomorphic-hand* condition, where the avatar has an anthropomorphic cartoon hand (see Figure 1);
- *Stick-fingers* condition, where the avatar has a non-anthropomorphic hand with sticks as fingers (see Figure 1).

Because we are forced to have movements due to the study of the SoA, we could not use visuo-tactile asynchrony. In this way, we decided to change the appearance of the avatar's hand to alter the SoBO like previous studies [AHTL16, LJ16, CHLL18]. In their experiment, Lin and Jörg showed that a SoBO can be created with different realistic representation of a hand, being a realistic hand, a toony or very toony hand, a zombie or robotic hand or even a wooden block [LJ16]. Nevertheless, the effect is the weakest for the non-anthropomorphic block model. Moreover, it has been shown that in order to induce ownership toward an external object, a basic morphological similarity with the real body part (or whole body) is needed [AR03, TCJF10, TH05].

We expect the SoBO to be lower with a non-anthropomorphic hand, similar to the wooden block in [LJ16]'s experiment. Since we wanted participants to perform hand movements and more specifically fingers movements, this non-anthropomorphic hand needed to have "fingers" for the user to be able to reflect upon their movements. We thus decided to have 5 "sticks" as fingers, aligned (i.e., there was no "thumb-like" position for any of the sticks) and floating in front of the avatar's wrist (see Figure 1). Moreover, the sticks are not attached to the wrist to make it less anthropomorphic (as a SoBO was possible with a robotic hand in [LJ16]).

On the contrary, in the condition where a high ownership illusion was expected we choose to use an anthropomorphic cartoon hand (see Figure 1). This was preferred over a realistic hand for two reasons. The first one being that an uncanny valley effect can exist to a certain extent, and the second being that otherwise, the virtual hand would have to match the shape of the hand and skin colour of each participant to not be a potential impacting factor [Mor12, LLL15]. It has also been found that a SoA is still possible for less realistic hands [AHTL16]. In 3*PP-PP* and 3*PP-EP* conditions, the user could in addition see the avatar's head (only if they turned their head, which they were instructed not to do). Still, as a safety measure, the avatar had a hood covering all his head, such that the avatar's face could never be seen from a 3PP (see Figure 1).

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

3.3. Design and Hypotheses

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

H1 Higher score in *Synchronous* over *Manipulated* [JAAL18].
H2 No difference between *Anthropomorphic-hand* and *Stick-fingers* [AHTL16, LJ16, CHLL18].
H3 No difference between 1*PP*, 3*PP-PP* or 3*PP-EP* [DBC*06].

Our hypotheses regarding the **SoSL score** were:

H4 No difference between *Synchronous* and *Manipulated* [DBC*06].
H5 No difference between *Anthropomorphic-hand* and *Stick-fingers*.
H6 Higher score in 1*PP* compared to the two 3PP conditions [MS14].

Finally, our hypotheses regarding the **SoBO score** were:

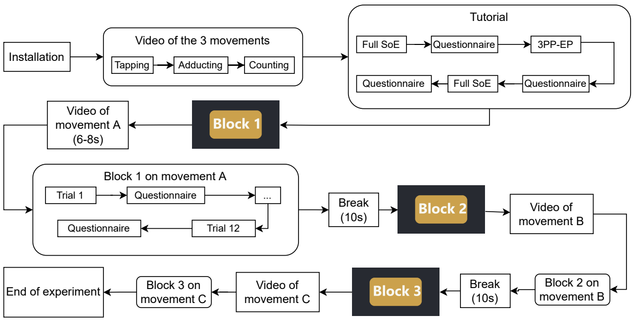

Figure 2: *Experimental protocol. The "Full SoE" condition in the tutorial represents the Synchronous and Anthropomorphic-hand and 1PP condition together. Movement A, B and C are the three movements (tapping, adducting and counting) counter-balanced between the participants in order to avoid any order effect.*

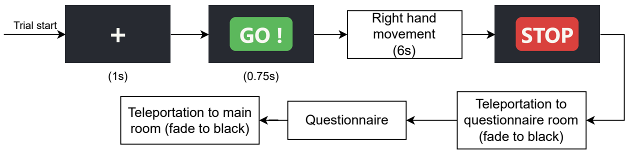

Figure 3: *Workflow of a trial. Participants had to repeat the movement, while looking at their virtual right-hand until a signal STOP was displayed 6s after the GO signal.*

H7 Higher score in *Synchronous* over *Manipulated* [KE12].
H8 Higher score in *Anthropomorphic-hand* over *Stick-fingers* [LJ16, AHTL16, PE08].
H9 No difference between 1*PP* and 3*PP-PP* and a higher score in 1*PP* over 3*PP-EP*.

3.4. Apparatus

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

3.5. Experimental protocol

Participants had to fill and sign an informed consent form before the experimental protocol was explained to them. All participants were provided with the exact same written instructions, which indicated that they would have to perform three blocks of 5 minutes each, each block associated to a different movement type (either tapping, abducting/adducting the fingers or counting as in [JAAL18] – in order to introduce variability in the experiment, without considering the movement type as an impacting factor). The *experimental* VE was a virtual room where participants were embodied in an avatar seated in front of a table ($205cm \times 75cm \times 67cm$). In front of them, a TV hanged on the wall ($1.60m$ from the virtual body, $158cm \times 0.85cm$), on which videos and signals were displayed (see Figure 1). The experimental protocol is depicted in Figure 2.

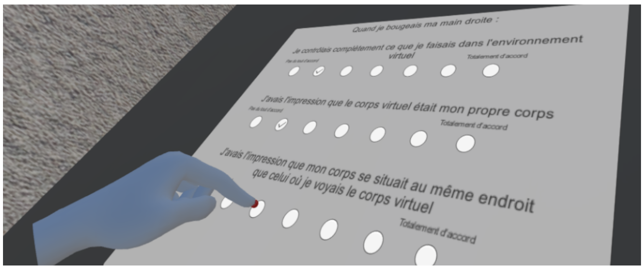

Figure 4: *Questionnaire being filled in VR with the left-hand using the standard Oculus hand representation and no avatar.*

After the explanation of the experiment, the VR headset was installed. The experiment first started by displaying videos of the different right-hand movements participants would have to perform. Participants could repeat them while the video was playing, and were corrected if the movement was done improperly. Then, participants had to perform a small tutorial of 3 trials (see next paragraph) in order to introduce them to the experimental protocol and to get used to the VE. Finally, once all remaining questions from the participants were answered by the experimenter, the experiment consisting of 3 blocks of 12 trials each started (see Figure 2 and 3).

Participants could take a break between blocks if they wanted to. On average, it took 40 minutes for each participant to complete the whole experiment (including explanations). In total, participants performed 36 trials (3 blocks × 12 trials), resulting in 3 trials per condition. The movement associated with each block, as well as the order of the 12 conditions within a block were counter-balanced between the participants in order to avoid any order effect. The only fixed parameter was the first trial of each block being a “full embodiment” condition (*Synchronous* and *Anthropomorphic-hand* and 1*PP*) to get a reference for other trials.

The tutorial’s aim was to get the participants used to the SoSL manipulation, i.e changing the visuospatial perspective. Indeed, as trials are only 6s long, it could be unsettling for some people the first time in a third-person perspective. The tutorial consisted in 3 (non-recorded) predetermined trials using the tapping movement: the first trial was a “full embodiment” condition; the second trial was only altering the SoSL by putting participants in the 3*PP-EP* condition; then a third trial in “full embodiment” again.

3.6. Subjective Measures

Most VR experiments about virtual embodiment use a questionnaire after each condition to assess the level of embodiment of the participant. Usually, the questionnaire is inspired from Botvinick and Cohen’s RHI experiment [BC98], but there are also questionnaires designed for the SoE [RL20, PGF21]. These questionnaires usually contain multiple questions for each component of the SoE. Given the number of trials and conditions we wanted to test, it was impossible to have our participants fill-in this kind of questionnaire after each of the 12 conditions.

As a consequence, we followed the procedure used in Jeunet et al. [JAAL18] to evaluate the SoE after each condition. After each trial, participants were asked to answer in VR 3 questions only, one to evaluate the SoA ("I was in full control of my actions in the virtual environment"), one to evaluate the SoSL ("I felt as if my body was located where I saw the virtual body"') and one to evaluate the SoBO ("I felt as if the virtual body was my body"). These questions were inspired or taken from existing questionnaires [BC98, JAAL18, HBC*20, PGF21]. The questions were preceded by "When I moved my right hand" to make sure participants rated their SoE during the hand movement only. For each question, participants answered on a 7-point Likert scale from "Strongly disagree" to "Strongly agree" with no label in between.

Participants answered the questionnaire directly in VR in another virtual room, with their left hand, with only an Oculus hand appearing in the VE (and no avatar – see Figure 4 – and the Oculus left hand was never shifted regardless of the *SoSL-manipulation* level) as to not alter the feeling of the trial. Participants were asked to try to keep their right hand posture while answering the questionnaire to be ready to start for the next trial.

4. Results

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

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

The 3 dependent variables were: the SoA score (*s_soa*), the SoSL score (*s_sosl*) and the SoBO score (*s_sobo*). For each of the 12 conditions, the score is defined as the mean of the 3 trials performed in this condition (1 per block). This ensures the assumption of independence of the ANOVA is met. Because the questionnaire and experimental design are similar to [JAAL18], we performed the same analysis. In the end, for each participant, there are 3 SoE components $\times 12$ conditions $= 36$ scores.

4.1. Impact of the Manipulations on the SoA Score

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

The ANOVA reveals a significant main effect of *SoA-manipulation* ($F(1,46) = 360.48$; $p < 0.001$; $\eta_p^2 = 0.887$), *SoSL-manipulation* ($F(1.75, 80.35) = 4.96$; $p < 0.05$; $\eta_p^2 = 0.097$) and *SoBO-manipulation* ($F(1,46) = 42.27$; $p < 0.001$; $\eta_p^2 = 0.479$) on the SoA score. Post-hoc tests indicate that the mean SoA score in 1*PP* ($M = 4.395$; $SD = 1.643$) is significantly higher than in 3*PP-EP* ($M = 4.092$; $SD = 1.498$) ($p < 0.05$). The *SoA-manipulation* $\times$ *SoSL-manipulation* interaction is significant ($F(2,92) = 4.73$; $p < 0.05$; $\eta_p^2 = 0.093$). Pairwise comparisons reveal a significant difference only in the *Synchronous* condition between 1*PP* and 3*PP-PP* ($t = 3.313$; $p < 0.05$) and between 1*PP* and 3*PP-EP* ($t = 3.932$; $p < 0.01$) (see Figure 5). The *SoA-manipulation* $\times$ *SoBO-manipulation* interaction is also significant ($F(1,46) = 27.45$; $p < 0.001$; $\eta_p^2 = 0.374$). Pairwise comparisons reveal a significant difference between *Anthropomorphic-hand* and *Stick-fingers* only in the *Synchronous* condition ($t = 7.562$; $p < 0.001$) (see Figure 5).

4.2. Impact of the Manipulations on the SoSL Score

The dependent variable in this ANOVA was the average SoSL score. A Shapiro-Wilk test revealed a violation of the assumption of normality. Yet, these parametric methods are known for their robustness regarding non-normally distributed data when applied to Likert-scales [MA17, Nor10]. The sphericity assumption was violated according to Mauchly's test for the *SoSL-manipulation* ($p < 0.0001$) variable, *SoA-manipulation***SoSL-manipulation* ($p < 0.01$) and *SoBO-manipulation***SoSL-manipulation* ($p < 0.05$) interactions. Thus, the degrees of freedom were corrected using the Huynh-Feldt correction.

The ANOVA revealed a significant main effect of *SoA-manipulation* ($F(1,46) = 21.04$; $p < 0.001$; $\eta_p^2 = 0.314$), *SoSL-manipulation* ($F(1.45, 66.48) = 215.74$; $p < 0.001$; $\eta_p^2 = 0.824$) and *SoBO-manipulation* ($F(1,46) = 14.30$; $p < 0.001$; $\eta_p^2 = 0.237$) on the SoSL score. Post-hoc tests indicate that the mean SoSL score in 1*PP* ($M = 5.787$; $SD = 1.231$) is significantly higher than in 3*PP-PP* ($M = 2.987$; $SD = 1.394$) which itself is significantly higher than in 3*PP-EP* ($M = 2.036$; $SD = 1.276$) ($p < 0.001$). The *SoA-manipulation* $\times$ *SoSL-manipulation* interaction is significant ($F(1.72, 79.25) = 5.29$; $p < 0.01$; $\eta_p^2 = 0.103$). Pairwise comparisons show a significant difference only in the 1*PP* condition between *Synchronous* and *Manipulated* ($t = 5.989$; $p < 0.05$) (see Figure 6). The *SoSL-manipulation* $\times$ *SoBO-manipulation* interaction is also significant ($F(1.82, 83.92) = 8.73$; $p < 0.001$; $\eta_p^2 = 0.159$). Pairwise comparisons reveal a significant difference between *Anthropomorphic-hand* and *Stick-fingers* only in the 1*PP* condition ($t = 5.523$; $p < 0.001$) (see Figure 6).

4.3. Impact of the Manipulations on the SoBO Score

Here, the dependent variable was the average SoBO score. A Shapiro-Wilk test revealed a violation of the assumption of normality but as mentioned above ANOVAs are robust in our case. According to Mauchly's test, the sphericity assumption was violated for the *SoSL-manipulation* variable ($p < 0.001$). Thus, the degree of freedom was corrected using the Huynh-Feldt correction.

The ANOVA revealed a significant main effect of *SoA-manipulation* ($F(1,46) = 105.56$; $p < 0.001$; $\eta_p^2 = 0.696$), *SoSL-manipulation* ($F(1.54, 70.84) = 56.12$; $p < 0.001$; $\eta_p^2 = 0.550$) and *SoBO-manipulation* ($F(1,46) = 96.69$; $p < 0.001$; $\eta_p^2 = 0.678$) on the SoBO score. Post-hoc tests indicate that the mean

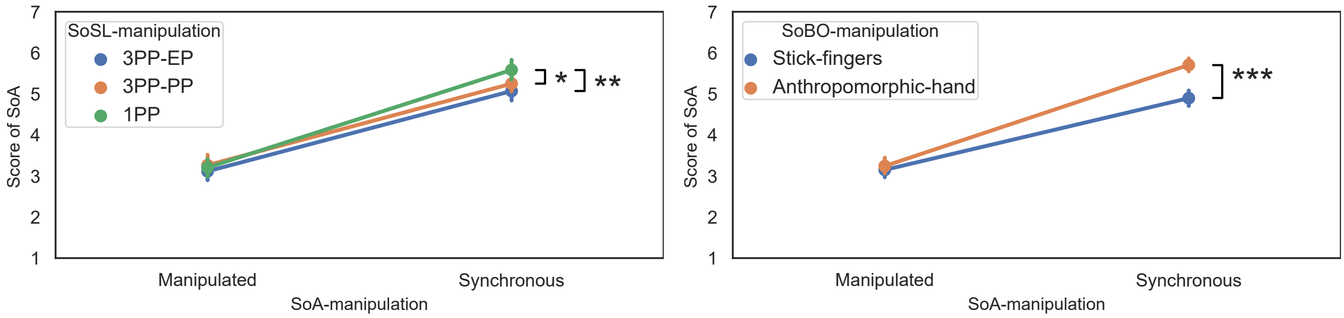

Figure 5: *Interaction between SoA-manipulation and (left) SoSL-manipulation; (right) SoBO-manipulation on the SoA score.*

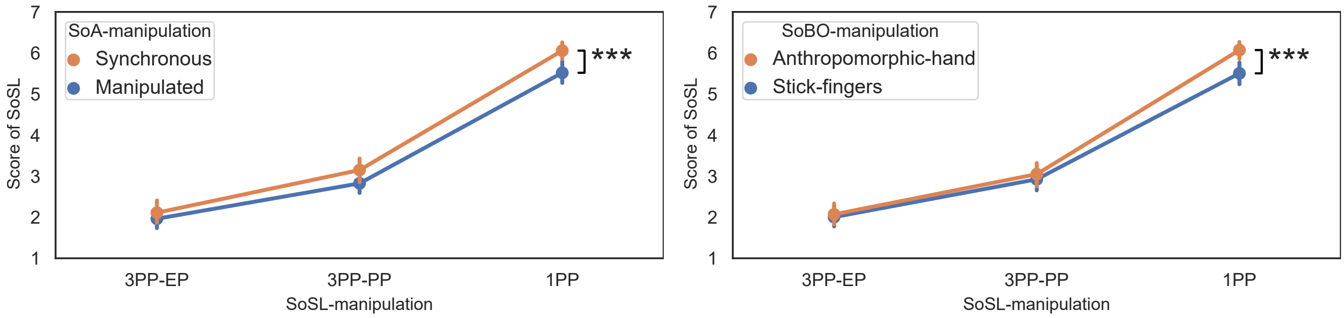

Figure 6: *Interaction between SoA-manipulation and (left) SoSL-manipulation; (right) SoBO-manipulation on the SoSL score.*

SoSL score in 1*PP* ($M = 4.048$; $SD = 1.723$) is significantly higher than in 3*PP-PP* ($M = 3.427$; $SD = 1.556$) which itself is significantly higher than in 3*PP-EP* ($M = 3.066$; $SD = 1.517$) ($p < 0.001$). The *SoA-manipulation* × *SoSL-manipulation* interaction is significant ($F(2,92) = 6.56$; $p < 0.01$; $\eta_p^2 = 0.125$). The *SoA-manipulation* × *SoBO-manipulation* interaction is also significant ($F(1,46) = 24.29$; $p < 0.001$; $\eta_p^2 = 0.346$). Finally, the *SoA-manipulation* × *SoSL-manipulation* × *SoBO-manipulation* interaction is significant ($F(1.98,91.15) = 3.24$; $p < 0.05$; $\eta_p^2 = 0.066$) (see Figure 7).

5. Discussion

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

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

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

5.1. Interaction between SoA and SoSL

Results revealed that the *SoA-manipulation* interacts with the *SoSL-manipulation* (see Figure 5 and Figure 6). These results contradicts **H3** and **H4**. Indeed, post-hoc tests showed that the *SoSL-manipulation* alters the user's SoA but only in the *Synchronous* condition (with a large effect size). In the current study, it could be argued that in the *Manipulated* condition, the SoA may be too low for the *SoSL-manipulation* to have an effect. There were also no significant difference in the *Synchronous* condition between 3*PP-PP* and 3*PP-EP*, so shifting the user's point of view by just 20 cm to the right might be already enough to alter the SoA. Likewise, results revealed that the *SoA-manipulation* has an effect on participants' SoSL only in 1*PP* condition. This again could be explained by the fact that in the 3*PP-PP* and 3*PP-EP* conditions, the SoSL may be too low to be impacted by the *SoA-manipulation*.

5.2. Interaction between SoA and SoBO

Interaction analysis and post-hoc tests showed that the *SoA-manipulation* interacts with the *SoBO-manipulation* (see Figure 5). This contradicts hypothesis **H2** but supports hypothesis **H7**. Indeed, we did not expect the *SoBO-manipulation* to alter the user's SoA, but this occurred in the *Synchronous* condition (with a large effect size). This is coherent with [CHLL18]'s results stating that the relationship between the SoA and the SoBO may vary depending on the experimental conditions. This could be explained by the fact that in the *Manipulated* condition, the SoA score is already too low for the *SoBO-manipulation* to have an effect. Bottom-up factors might have a stronger effect than top-down factors: the *SoBO-manipulation* targets cognitive processes while

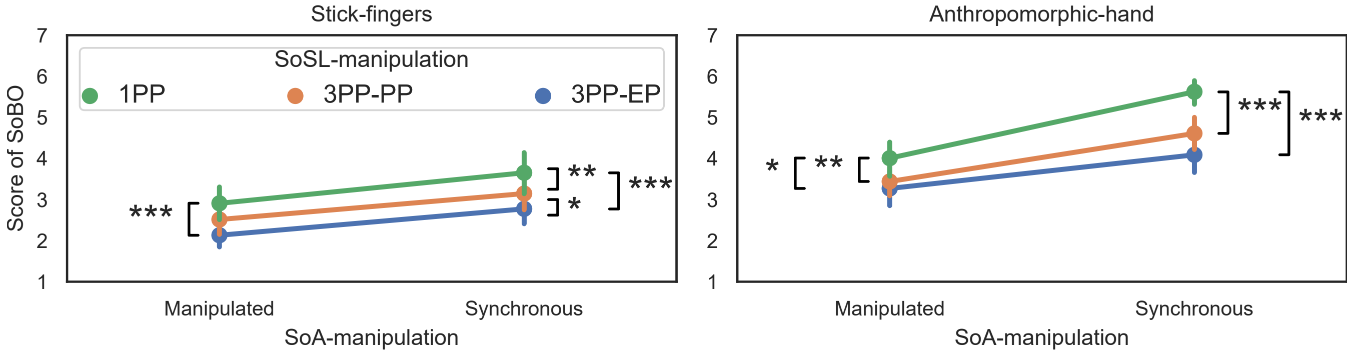

Figure 7: *Interaction between SoA-manipulation, SoSL-manipulation and SoBO-manipulation on the SoBO score.*

the *SoA-manipulation* leads to incongruent stimuli at the perceptual level (the visual cues do not match the perceptual cues produced by the actual movement) [LW22]. Likewise, results revealed the *SoA-manipulation* has an effect on participants' SoBO score with a large effect size, supporting **H7**. These results reinforce the idea that the SoBO and SoA are dependent.

5.3. Interaction between SoBO and SoSL

Interaction analysis and post-hoc tests showed that the *SoBO-manipulation* interacts with the *SoSL-manipulation*. We hypothesised that the *SoSL-manipulation* would impact the SoBO score only in 3*PP-EP* (**H9**). Indeed, we expected to find the same results as in Maselli and Slater's experiment [MS14] but it was not the case. While there is a difference between 1*PP* and 3*PP-EP*, we also observed a difference between 1*PP* and 3*PP-PP* in all conditions except in the *Stick-fingers+Manipulated* condition, and thus we do not validate **H9** nor replicate [MS14]'s results. Likewise, results showed that the *SoBO-manipulation* altered the user's SoSL, but only in the 1*PP* condition, which contradicts hypothesis **H5**.

5.4. Limitations

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

In this experiment, we used a non-anthropomorphic hand (the *Stick-fingers* condition) with five aligned stick fingers (i.e. without a thumb) instead of a robotic hand [LJ16] or a wooden block [LJ16] to alter the hand realism, because we needed hand and finger movements. Since this kind of hand has, to the best of our knowledge, not been used before, we do not know how it impacts the SoA. This hand could be perceived as inaccurate due to the incorrect position of the thumb, thus influencing the SoA. However, it is still unclear how the SoA is impacted by hand appearance, as sometimes it was shown to have an impact [AHTL16] and sometimes not [LJ16]. We cannot conclude if the influence of hand realism on SoA in our experiment is due to the hand appearance or to the sticky fingers looking inaccurate. Nevertheless, the movements were not meant to be perfectly executed and we believe that this "sticky thumb" is not the cause of the impact of realism on the SoA. In most post-experiment verbal reports, participants indicated to be disturbed more by SoA manipulations even in the Stick-Fingers condition than by the hand realism. It remains an open question for future work.

Another limitation of this study is the short amount of exposure time. Indeed, each trial was only 6s long. It can thus be questioned if there were any sort of embodiment experienced by participants. With so many conditions, it was not feasible to have long exposition time for each condition with some repetitions, this is why we followed [JAAL18]'s experimental design. Participants however had to perform a tutorial first, in which they could get used to the virtual body and the hand tracking system. Moreover, in post experiment verbal reports, participants mostly reported to feel embodied during the experiment. Also, all manipulations relied on visual feedback, so participants could perceive the differences directly.

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

Finally, as mentioned in subsection 3.6, we could not use standardised SoE questionnaires [RL20, PGF21] after each condition and relied on the method from [JAAL18]'s experiment. This hinders comparability with other experiments since SoE scores could not be calculated. However, our questions were taken from existing validated questionnaires, and more importantly, in this within-subject experiment we were more interested in differences between the conditions to better understand the interactions between the components. Further experiments should explore other experimental designs in order to include these standardised questionnaires.

6. Conclusion

The presented experiment explored the relationships and interactions between the SoA, the SoSL and the SoBO. We were able to confirm previous results like the link between SoA/SoBO and SoBO/SoSL. Moreover, we observed that the SoSL and SoA seem to be not independent, and this is, we believe, the first experiment investigating the link between the SoSL and the SoA in VR scenarios. Finally, we confirmed that the three components are all interrelated regarding the SoBO score. Nevertheless, additional studies are required to explore the relationship between the components and better understanding the factors impacting them.

References

[AHTL16] Argelaguet F., Hoyet L., Trico M., Lecuyer A.: The role of interaction in virtual embodiment: Effects of the virtual hand representation. In *2016 IEEE Virtual Reality (VR)* (Greenville, SC, USA, Mar. 2016), IEEE, pp. 3–10. URL: http://ieeexplore.ieee.org/document/7504682/, doi:10.1109/VR.2016.7504682. 2, 3, 4, 5, 8

[AR03] Armel K. C., Ramachandran V. S.: Projecting sensations to external objects: evidence from skin conductance response. *Proceedings of the Royal Society of London. Series B: Biological Sciences 270*, 1523 (July 2003), 1499–1506. URL: https://royalsocietypublishing.org/doi/10.1098/rspb.2003.2364, doi:10.1098/rspb.2003.2364. 4

[ASK20] Atkinson S., Stolz A., Kennedy H. W.: The Future of Film Report 2020. Publisher: King's College London. doi:10.18742/PUB01-020. 2

[BBOS17] Bourdin P., Barberia I., Oliva R., Slater M.: A Virtual Out-of-Body Experience Reduces Fear of Death. *PLOS ONE 12*, 1 (Jan. 2017), e0169343. URL: https://dx.plos.org/10.1371/journal.pone.0169343, doi:10.1371/journal.pone.0169343. 2

[BC98] Botvinick M., Cohen J.: Rubber hands 'feel' touch that eyes see. *Nature 391*, 6669 (Feb. 1998), 756–756. URL: http://www.nature.com/articles/35784, doi:10.1038/35784. 3, 4, 5, 6

[BDS*18] Braun N., Debener S., Spychala N., Bongartz E., Sörös P., Müller H. H. O., Philipsen A.: The Senses of Agency and Ownership: A Review. *Frontiers in Psychology 9* (2018). Publisher: Frontiers. URL: https://www.frontiersin.org/articles/10.3389/fpsyg.2018.00535/full, doi:10.3389/fpsyg.2018.00535. 2, 3

[BGB*15] Bouville R., Gouranton V., Boggini T., Nouviale F., Arnaldi B.: #FIVE : High-level components for developing collaborative and interactive virtual environments. In *2015 IEEE 8th Workshop on Software Engineering and Architectures for Realtime Interactive Systems (SEARIS)* (Mar. 2015), pp. 33–40. ISSN: 2328-7829. doi:10.1109/SEARIS.2015.7854099. 2

[BLSS04] Blanke O., Landis T., Spinelli L., Seeck M.: Out-of-body experience and autoscopy of neurological origin. *Brain 127*, 2 (Feb. 2004), 243–258. URL: https://academic.oup.com/brain/article-lookup/doi/10.1093/brain/awh040, doi:10.1093/brain/awh040. 2

[BM09] Blanke O., Metzinger T.: Full-body illusions and minimal phenomenal selfhood. *Trends in Cognitive Sciences 13*, 1 (Jan. 2009), 7–13. URL: https://linkinghub.elsevier.com/retrieve/pii/S1364661308002507, doi:10.1016/j.tics.2008.10.003. 2

[CHLL18] Chen W.-Y., Huang H.-C., Lee Y.-T., Liang C.: Body ownership and the four-hand illusion. *Scientific Reports 8*, 1 (Dec. 2018), 2153. URL: http://www.nature.com/articles/s41598-018-19662-x, doi:10.1038/s41598-018-19662-x. 3, 4, 7

[DBC*06] David N., Bewernick B. H., Cohen M. X., Newen A., Lux S., Fink G. R., Shah N. J., Vogeley K.: Neural Representations of Self versus Other: Visual-Spatial Perspective Taking and Agency in a Virtual Ball-tossing Game. *Journal of Cognitive Neuroscience 18*, 6 (June 2006), 898–910. URL: https://direct.mit.edu/jocn/article/18/6/898-910/4153, doi:10.1162/jocn.2006.18.6.898. 3, 4

[Dew21] Dewez D.: *Towards Avatar-Based Interaction in Virtual Reality*. PhD Thesis, L'INSTITUT NATIONAL DES SCIENCES APPLIQUÉES RENNES, 2021. 2

[DMI*18] Dwyer T., Marriott K., Isenberg T., Klein K., Riche N., Schreiber F., Stuerzlinger W., Thomas B. H.: Immersive Analytics: An Introduction. In *Immersive Analytics*, Marriott K., Schreiber F., Dwyer T., Klein K., Riche N. H., Itoh T., Stuerzlinger W., Thomas B. H., (Eds.), vol. 11190. Springer International Publishing, Cham, 2018, pp. 1–23. Series Title: Lecture Notes in Computer Science. URL: http://link.springer.com/10.1007/978-3-030-01388-2_1, doi:10.1007/978-3-030-01388-2_1. 2

[dV11] de Vignemont F.: Embodiment, ownership and disownership. *Consciousness and Cognition* (2011), 12. 2

[Ehr07] Ehrsson H. H.: The Experimental Induction of Out-of-Body Experiences. *Science 317*, 5841 (Aug. 2007), 1048–1048. URL: https://www.sciencemag.org/lookup/doi/10.1126/science.1142175, doi:10.1126/science.1142175. 2

[EMFM21] Eubanks J. C., Moore A. G., Fishwick P. A., McMahan R. P.: A Preliminary Embodiment Short Questionnaire. *Frontiers in Virtual Reality 2* (2021). Publisher: Frontiers. URL: https://www.frontiersin.org/articles/10.3389/frvir.2021.647896/full, doi:10.3389/frvir.2021.647896. 2

[Fri20] Fribourg R.: *Contribution to the study of factors influencing the sense of embodiment towards avatars in virtual reality*. PhD Thesis, Rennes 1, 2020. 2

[Gal00] Gallagher S.: Philosophical conceptions of the self: implications for cognitive science. *Trends in Cognitive Sciences 4*, 1 (Jan. 2000), 14–21. URL: https://linkinghub.elsevier.com/retrieve/pii/S1364661399014175, doi:10.1016/S1364-6613(99)01417-5. 2

[Hag17] Haggard P.: Sense of agency in the human brain. *Nature Reviews Neuroscience 18*, 4 (Apr. 2017), 196–207. Number: 4 Publisher: Nature Publishing Group. URL: https://www.nature.com/articles/nrn.2017.14, doi:10.1038/nrn.2017.14. 2

[HBC*20] Hurault J.-C., Broc G., Crône L., Tedesco A., Brunel L.: Measuring the Sense of Agency: A French Adaptation and Validation of the Sense of Agency Scale (F-SoAS). *Frontiers in Psychology 11* (2020), 2650. URL: https://www.frontiersin.org/article/10.3389/fpsyg.2020.584145, doi:10.3389/fpsyg.2020.584145. 6

[Hun07] Hunter J. D.: Matplotlib: A 2d graphics environment. *Computing in Science & Engineering 9*, 3 (2007), 90–95. doi:10.1109/MCSE.2007.55. 6

[IdKH06] IJsselsteijn W. A., de Kort Y. A. W., Haans A.: Is This *My* Hand I See Before Me? The Rubber Hand Illusion in Reality, Virtual Reality, and Mixed Reality. *Presence: Teleoperators and Virtual Environments 15*, 4 (Aug. 2006), 455–464. URL: https://www.mitpressjournals.org/doi/abs/10.1162/pres.15.4.455, doi:10.1162/pres.15.4.455. 3

[JAAL18] Jeunet C., Albert L., Argelaguet F., Lecuyer A.: "Do You Feel in Control?": Towards Novel Approaches to Characterise, Manipulate and Measure the Sense of Agency in Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics 24*, 4 (Apr. 2018), 1486–1495. URL: http://ieeexplore.ieee.org/document/8260944/, doi:10.1109/TVCG.2018.2794598. 2, 3, 4, 5, 6, 8

[KBS13] Kilteni K., Bergstrom I., Slater M.: Drumming in Immersive Virtual Reality: The Body Shapes the Way We Play. *IEEE TRANSACTIONS ON VISUALIZATION AND COMPUTER GRAPHICS 19*, 4 (2013), 9. 2

[KE12] Kalckert A., Ehrsson H. H.: Moving a Rubber Hand that Feels Like Your Own: A Dissociation of Ownership and Agency. *Frontiers in Human Neuroscience 6* (2012). Publisher: Frontiers. URL: https://www.frontiersin.org/articles/10.3389/fnhum.2012.00040/full, doi:10.3389/fnhum.2012.00040. 3, 5

[KGS12] Kilteni K., Groten R., Slater M.: The Sense of Embodiment in Virtual Reality. *Presence: Teleoperators and Virtual Environments 21*, 4 (Nov. 2012), 373–387. URL: https:

//www.mitpressjournals.org/doi/abs/10.1162/PRES_a_00124, doi:10.1162/PRES_a_00124. 2

[KIS*15] KANG S. Y., IM C.-H., SHIM M., NAHAB F. B., PARK J., KIM D.-W., KAKAREKA J., MILETTA N., HALLETT M.: Brain Networks Responsible for Sense of Agency: An EEG Study. *PLOS ONE 10*, 8 (Aug. 2015), e0135261. Publisher: Public Library of Science. URL: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0135261, doi:10.1371/journal.pone.0135261. 2

[Lin20] LINDNER P.: Better, Virtually: the Past, Present, and Future of Virtual Reality Cognitive Behavior Therapy. *International Journal of Cognitive Therapy* (Oct. 2020). URL: http://link.springer.com/10.1007/s41811-020-00090-7, doi:10.1007/s41811-020-00090-7. 2

[LJ16] LIN L., JÖRG S.: Need a hand?: how appearance affects the virtual hand illusion. In *Proceedings of the ACM Symposium on Applied Perception* (Anaheim California, July 2016), ACM, pp. 69–76. URL: https://dl.acm.org/doi/10.1145/2931002.2931006, doi:10.1145/2931002.2931006. 3, 4, 5, 8

[LLL15] LUGRIN J.-L., LATT J., LATOSCHIK M. E.: Anthropomorphism and Illusion of Virtual Body Ownership. *ICAT-EGVE 2015 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments* (2015), 8 pages. Artwork Size: 8 pages ISBN: 9783905674842 Publisher: The Eurographics Association. URL: https://diglib.eg.org/handle/10.2312/egve20151303, doi:10.2312/EGVE.20151303. 3, 4

[LTMB07] LENGGENHAGER B., TADI T., METZINGER T., BLANKE O.: Video Ergo Sum: Manipulating Bodily Self-Consciousness. *Science 317*, 5841 (Aug. 2007), 1096–1099. URL: https://www.sciencemag.org/lookup/doi/10.1126/science.1143439, doi:10.1126/science.1143439. 2, 3

[LW22] LATOSCHIK M. E., WIENRICH C.: Congruence and Plausibility, not Presence?! Pivotal Conditions for XR Experiences and Effects, a Novel Model. *Frontiers in Virtual Reality 3* (June 2022), 694433. arXiv:2104.04846 [cs]. URL: http://arxiv.org/abs/2104.04846, doi:10.3389/frvir.2022.694433. 8

[MA17] MIRCIOIU C., ATKINSON J.: A Comparison of Parametric and Non-Parametric Methods Applied to a Likert Scale. *Pharmacy 5*, 2 (June 2017), 26. Number: 2 Publisher: Multidisciplinary Digital Publishing Institute. URL: https://www.mdpi.com/2226-4787/5/2/26, doi:10.3390/pharmacy5020026. 6

[Mor12] MORI M.: The uncanny valley (1970). *Energy 7*, 4 (2012), 33–35. 3, 4

[MS14] MASELLI A., SLATER M.: Sliding perspectives: dissociating ownership from self-location during full body illusions in virtual reality. *Frontiers in Human Neuroscience 8* (Sept. 2014). URL: http://journal.frontiersin.org/article/10.3389/fnhum.2014.00693/abstract, doi:10.3389/fnhum.2014.00693. 3, 4, 8

[NGSS11] NORMAND J.-M., GIANNOPOULOS E., SPANLANG B., SLATER M.: Multisensory Stimulation Can Induce an Illusion of Larger Belly Size in Immersive Virtual Reality. *PLoS ONE 6*, 1 (Jan. 2011), e16128. URL: https://dx.plos.org/10.1371/journal.pone.0016128, doi:10.1371/journal.pone.0016128. 2

[Nor10] NORMAN G.: Likert scales, levels of measurement and the "laws" of statistics. *Advances in Health Sciences Education 15*, 5 (Dec. 2010), 625–632. URL: https://doi.org/10.1007/s10459-010-9222-y, doi:10.1007/s10459-010-9222-y. 6

[PE08] PETKOVA V. I., EHRSSON H. H.: If I Were You: Perceptual Illusion of Body Swapping. *PLoS ONE 3*, 12 (Dec. 2008), e3832. URL: https://dx.plos.org/10.1371/journal.pone.0003832, doi:10.1371/journal.pone.0003832. 3, 5

[PGF21] PECK T. C., GONZALEZ-FRANCO M.: Avatar Embodiment. A Standardized Questionnaire. *Frontiers in Virtual Reality 1* (2021). Publisher: Frontiers. URL: https://www.frontiersin.org/articles/10.3389/frvir.2020.575943/full?utm_source=S-TWT&utm_medium=SNET&utm_campaign=ECO_FRVIR_XXXXXXXX_auto-dlvrit, doi:10.3389/frvir.2020.575943. 2, 5, 6, 8

[PGFSV*16] PADRAO G., GONZALEZ-FRANCO M., SANCHEZ-VIVES M. V., SLATER M., RODRIGUEZ-FORNELLS A.: Violating body movement semantics: Neural signatures of self-generated and external-generated errors. *NeuroImage 124* (Jan. 2016), 147–156. URL: https://linkinghub.elsevier.com/retrieve/pii/S1053811915007314, doi:10.1016/j.neuroimage.2015.08.022. 2

[PKE11] PETKOVA V. I., KHOSHNEVIS M., EHRSSON H. H.: The Perspective Matters! Multisensory Integration in Ego-Centric Reference Frames Determines Full-Body Ownership. *Frontiers in Psychology 2* (2011). URL: http://journal.frontiersin.org/article/10.3389/fpsyg.2011.00035/abstract, doi:10.3389/fpsyg.2011.00035. 3

[PWL*14] PIRYANKOVA I. V., WONG H. Y., LINKENAUGER S. A., STINSON C., LONGO M. R., BÜLTHOFF H. H., MOHLER B. J.: Owning an Overweight or Underweight Body: Distinguishing the Physical, Experienced and Virtual Body. *PLoS ONE 9*, 8 (Aug. 2014), e103428. URL: https://dx.plos.org/10.1371/journal.pone.0103428, doi:10.1371/journal.pone.0103428. 2

[RFML20] RABELLINO D., FREWEN P. A., MCKINNON M. C., LANIUS R. A.: Peripersonal Space and Bodily Self-Consciousness: Implications for Psychological Trauma-Related Disorders. *Frontiers in Neuroscience 14* (2020). URL: https://www.frontiersin.org/article/10.3389/fnins.2020.586605. 4

[RL20] ROTH D., LATOSCHIK M. E.: Construction of a Validated Virtual Embodiment Questionnaire. *IEEE Transactions on Visualization and Computer Graphics 26*, 12 (Dec. 2020), 3546–3556. arXiv: 1911.10176. URL: http://arxiv.org/abs/1911.10176, doi:10.1109/TVCG.2020.3023603. 5, 8

[RSt20] RSTUDIO TEAM: *RStudio: Integrated Development Environment for R*. RStudio, PBC., Boston, MA, 2020. URL: http://www.rstudio.com/. 6

[SNB*14] SPANLANG B., NORMAND J.-M., BORLAND D., KILTENI K., GIANNOPOULOS E., POMÉS A., GONZÁLEZ-FRANCO M., PEREZ-MARCOS D., ARROYO-PALACIOS J., MUNCUNILL X. N., SLATER M.: How to Build an Embodiment Lab: Achieving Body Representation Illusions in Virtual Reality. *Frontiers in Robotics and AI 1* (2014). Publisher: Frontiers. URL: https://www.frontiersin.org/articles/10.3389/frobt.2014.00009/full, doi:10.3389/frobt.2014.00009. 2

[SPMESV09] SLATER M., PÉREZ MARCOS D., EHRSSON H., SANCHEZ-VIVES M.: Inducing illusory ownership of a virtual body. *Frontiers in Neuroscience 3* (2009), 29. URL: https://www.frontiersin.org/article/10.3389/neuro.01.029.2009, doi:10.3389/neuro.01.029.2009. 3

[SSSVB10] SLATER M., SPANLANG B., SANCHEZ-VIVES M. V., BLANKE O.: First Person Experience of Body Transfer in Virtual Reality. *PLoS ONE 5*, 5 (May 2010), e10564. URL: https://dx.plos.org/10.1371/journal.pone.0010564, doi:10.1371/journal.pone.0010564. 2

[TCJF10] TSAKIRIS M., CARPENTER L., JAMES D., FOTOPOULOU A.: Hands only illusion: multisensory integration elicits sense of ownership for body parts but not for non-corporeal objects. *Experimental Brain Research 204*, 3 (July 2010), 343–352. URL: http://link.springer.com/10.1007/s00221-009-2039-3, doi:10.1007/s00221-009-2039-3. 4

[TH05] TSAKIRIS M., HAGGARD P.: The Rubber Hand Illusion Revisited: Visuotactile Integration and Self-Attribution. *Journal of Experimental Psychology: Human Perception and Performance 31*, 1 (2005), 80–91. URL: http://doi.apa.org/getdoi.cfm?doi=10.

1037/0096-1523.31.1.80, doi:10.1037/0096-1523.31.1.80. 4

[TLH10] TSAKIRIS M., LONGO M. R., HAGGARD P.: Having a body versus moving your body: Neural signatures of agency and body-ownership. *Neuropsychologia 48*, 9 (July 2010), 2740–2749. URL: https://www.sciencedirect.com/science/article/pii/S0028393210002022, doi:10.1016/j.neuropsychologia.2010.05.021. 3

[TSBG07] TSAKIRIS M., SCHÜTZ-BOSBACH S., GALLAGHER S.: On agency and body-ownership: Phenomenological and neurocognitive reflections. *Consciousness and Cognition 16*, 3 (Sept. 2007), 645–660. URL: https://linkinghub.elsevier.com/retrieve/pii/S1053810007000542, doi:10.1016/j.concog.2007.05.012. 3

[Was21] WASKOM M. L.: seaborn: statistical data visualization. *Journal of Open Source Software 6*, 60 (2021), 3021. URL: https://doi.org/10.21105/joss.03021, doi:10.21105/joss.03021. 6

[YS10] YUAN Y., STEED A.: Is the rubber hand illusion induced by immersive virtual reality? In *2010 IEEE Virtual Reality Conference (VR)* (2010), pp. 95–102. doi:10.1109/VR.2010.5444807. 3