Do You Need Another Hand? Investigating Dual Body Representations During Anisomorphic 3D Manipulation

Diane Dewez, Ludovic Hoyet, Anatole Lécuyer, and Ferran Argelaguet

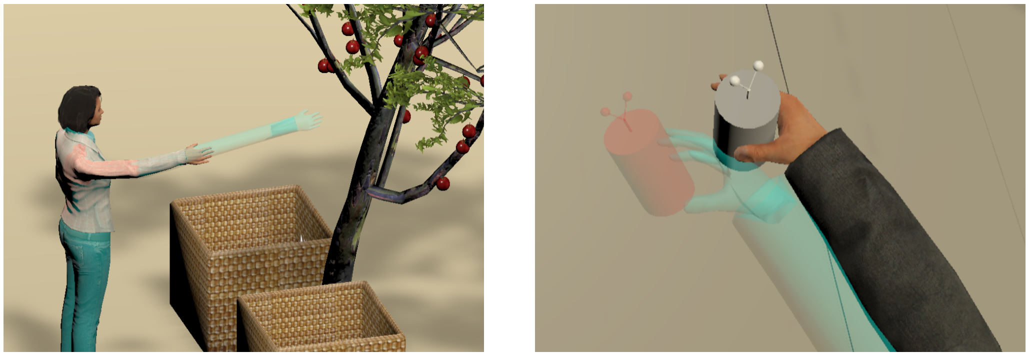

Fig. 1. Illustration of two types of dual body representation studied in this paper. On the left image, a ghost representation enables remote manipulation while a realistic co-located representation provides feedback with respect to the real user's position. On the right image, a ghost representation provides feedback with respect to the user's real position while a realistic representation enables precise manipulation with the environment thanks to slowed motion.

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 paper, 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 (with the Go-Go technique) and decreased motion (with the PRISM technique). Two visual appearances for the interactive representation and the co-located one were explored. This exploratory study investigating dual representations in this context showed that people globally preferred having a single representation, but opinions diverged for the Go-Go technique. Also, we could not find significant differences in terms of performance. 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.

Index Terms—Avatar, Sense of embodiment, Interaction, Virtual reality.

1 Introduction

Anisomorphic interaction techniques, i.e. techniques that alter users' input motion, are often used in Virtual Reality (VR). These techniques alter users' motion differently according to their own purpose. For example, the Go-Go technique [35] applies a gain to amplify users' motion and enables reaching distant objects. The motion can also be decreased to gain precision during fine manipulation [15], or sometimes even constrained to respect real-world physical constraints [36]. While these techniques have been widely used for several years with simple user representations, it remains unclear how the use of high-fidelity avatars would influence users' actions and body perception.

Nevertheless, representing users with high-fidelity avatars is common as they offer several advantages. Avatars were found to increase spatial awareness [9], or even to impact perceived effort during a physical task [23]. During cognitive tasks, the effect of seeing an avatar is not clear yet, as it was sometimes found helpful to reduce mental load [42] or having no effect on accuracy [33] depending on the task. There are also an increasing number of applications using full-body avatars, especially social VR applications. Because they cannot see their real body anymore, users can feel that this virtual representation of themselves is their real body [21]. This phenomenon is called the sense of embodiment, and VR developers usually want to maximize it to offer a better user experience. To maximize it, it was found that spatially and temporally congruent visuomotor stimulation, i.e. having an avatar moving according to users' movements, was an efficient method [24]. If movements are distorted during interaction, this could be detrimental to the sense of embodiment, as spatial congruency would not be respected anymore. While the dominance of vision over proprioception makes small offsets acceptable [3], bigger offsets can impact body perception [19]. In this case, the question arises as to which is the best visual feedback to apply motion distortion on users' avatar, to preserve both interaction efficiency and sense of embodiment [8]. To start answering this question, Feuchtner and Müller [13] investigated different avatar appearances when using the Go-Go technique in augmented reality. The preferred condition was an extended arm, as participants appreciated that it preserved body continuity. However, this type of feedback deformed the avatar and made users lose the feedback of their real motion.

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.

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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 [4,36], 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 [35], and precise manipulation with a gain that decreases movement [15]. 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 paper provides insight on which user representation to choose during 3D anisomorphic manipulation.

The structure of the paper is as follows. Section 2 presents the main related work on anisomorphic techniques, their impact on the sense of embodiment, and multiple body representations. The context and an overview of our experiments are presented in Section 3. Section 4 and 5 present the two conducted experiments focusing on amplified motion and decreased motion respectively. Section 6 concludes the paper with a global discussion on the use of dual representations, as well as perspectives for future research.

2 Related Work

In this section, we will present common techniques involving motion alteration, then the impact they can have on the sense of embodiment. Finally, we will present related work on extended avatars and dual representations. These are an open lead to explore towards reconciling embodiment and motion alteration.

2.1 Interaction Techniques Using Motion Alteration

Motion data captured from hand-held devices (e.g. VR controllers) can be modulated by the interaction technique in order to alter the user's interaction capabilities [15, 35]. Precisely, the Control-Display gain (CD gain) defines how users' motions are mapped to their virtual counterparts. The CD gain is a factor that will either increase (if it is greater than one) or decrease (if it is lower than one) users' motion. Only a CD gain of one will result in a total co-location of the real and virtual counterparts. For example, the Go-Go technique [35] enables remote object selection and manipulation by increasing the motion performed by the user, therefore increasing unrealistically the distance between the user's physical hand and the virtual hand. The gain can also be decreased, such as in the PRISM technique [15], to increase precision. If the displayed motion is slower than the real performed motion, it is possible to move objects more slowly, to translate or rotate them precisely. Motion distortion can also be used to provide haptic feedback by leading users to a physical prop [1]. This technique applies an offset to the virtual hand so users will reach the real tangible object. Movements can be distorted to assist users during a manipulation task by leading the virtual hand towards the virtual target [34], or even to reduce arm fatigue [14]. Globally, at a given time, motion can be either amplified or decreased during anisomorphic interaction.

2.2 Motion Alterations and the Sense of Embodiment

The medium through which motions are displayed to users is their virtual representation. While we start being able to represent users using high-quality full-body virtual humans, this type of representation might not be compatible with motion alteration as it imposes physical constraints (arm length, co-location with the real body). Using a high-fidelity avatar raises the question of which feedback should be used, for example when using increased motion with the Go-Go technique. Should we use a floating hand, or an elongated arm [13]? Depending on the feedback chosen, this might disturb users which could feel like their avatar is not their body. Nevertheless, it would be beneficial for user experience to keep the illusion that this virtual body, replacing users' real body not visible anymore because of the Head-Mounted Display (HMD), is their real body. This illusion, the sense of embodiment [21], is similar to the rubber hand illusion [2] in which participants can integrate a rubber hand as part of their body thanks to visuotactile stimulation. It is similar in VR but with a 3D virtual body [41], often seen from a first-person perspective. Users can feel that the avatar is part of their own body (sense of ownership), that they can control the avatar's movements (sense of agency) and that the avatar is co-located with their real body (sense of self-location) [21]. The most effective way to elicit embodiment is to use multisensory stimulation, such as congruent visuomotor or visuotactile stimulation [24]. The problem is that motion alterations break spatial congruency, which can potentially impact the sense of embodiment, especially the sense of agency [12, 19, 25]. In some cases where the alteration is done slowly, the impact can be limited on the sense of embodiment, for example the reaction to a threat can be as high as when there is no distortion [47]. It was also found that it can change body perception, for example predicting future motion and displaying it can give the illusion of having a lighter body [20], which can be wanted in some applications but not in others where motion is just altered for interaction.

Despite a growing literature on the relation between sense of embodiment and interaction, the impact of motion distortion has not been deeply investigated. Some studies tried to measure the noticeable perception thresholds for motion alterations. It was found to be influenced by the motion direction [11] or by avatar anthropomorphism [31]. The impact on virtual embodiment is however unclear. Additionally, these studies focused on cases where users saw only one virtual representation of their movements. We can wonder what would happen if users could see multiple representations of their movements during interaction.

2.3 Extended and Multiple Body Representations

Few studies have investigated virtual representations with additional body parts or full bodies. In this part, we will present these studies which investigated either extended or multiple body representations.

2.3.1 Extended Body Representations

Avatar extensions have been explored, such as human tails [43] or third arm [26]. 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. Elongated arms have also been studied [22], one study investigating its use in augmented reality while keeping a representation of the real arm [13]. 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 [44]. 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 the selection performance.

2.3.2 Multiple Body Representations

A study investigated the experience of having two bodies in VR, but neither spatially co-located nor interacting with the Virtual Environment (VE) [18]. Similar studies with additional body parts were conducted in real life with the rubber hand illusion [10], using video stream [5, 16] or augmented reality [37]. More recently, a study investigated "distributed embodiment", i.e. embodiment towards up to four bodies [30]. 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 [39]. Some VR applications have two superimposed representations, but they are usually used for guidance [46] 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 [46], where the second representation used for guidance is more transparent than the main one [6, 17].

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.

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 paper is the use of dual body 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 [27, 29] 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 of this paper is close to the ghost metaphor [46] 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 paper, 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 [35], and the PRISM technique which decreases movements to gain precision [15].

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 [35]. When using this technique, users' movements above a certain threshold are amplified, enabling both close and remote object manipulation.

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 performed using a desktop computer (Nvidia GeForce RTX 2080 Super, 32GB RAM, Intel(R) Xeon(R) W-2125 CPU), ensuring a minimum frame rate of 90fps under all conditions. The experiment was developed using Unity 2019.4.12f1. We used gender-matched avatars based on users' self-identification from the Rocketbox library. Avatars were not race-matched. They were animated using the RootMotion Final IK plugin. For object interaction (selection and hand poses), we used the SteamVR interaction system.

4.2 Go-Go Technique Implementation

Our implementation is based on the original Go-Go implementation [35]. 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:

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

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 Feuchtner and Müller [13]. This was the most stable solution, as it did not depend on the head orientation.

4.3 Tasks

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 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.

4.3.2 Additional Task: Maximum Reach Estimation Task

Interacting with remote objects can alter the mental arm representation, and give a sensation of real elongated arm [13]. We therefore decided to add a task to estimate whether the perceived maximum reach distance was influenced by the user 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 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 (Ø). For this experiment we chose three levels of *Representation*, defined as : R - Ø, R - G and G - R (see Figure 2). In R - Ø, 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 Ø - R could not be used in this experiment. The order of the different *Representations* was fully counterbalanced.

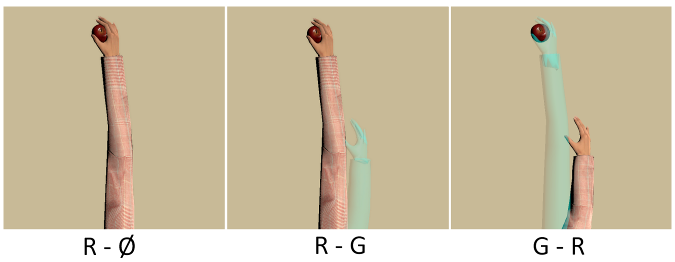

Fig. 2. The three levels of *Representation* in the first experiment with amplified motion. The interactive arm is either realistic (in R - Ø or R - G) or transparent (in G - R). When a co-located arm is displayed, a ghost representation (in R - G) or a realistic one (in G - R) is used.

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 the trigger again, 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.

4.5 Experimental Data

4.5.1 Subjective Measures

Participants' sense of embodiment was measured using the questionnaires from Peck and Gonzalez-Franco [32] (mentioned as PGF questionnaire hereafter) and from Roth and Latoschik [38] (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.

Table 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 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.

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 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 2). Subjects were also asked to rank the conditions in order of preference after the experiment, and to explain why they chose this order.

4.5.2 Objective Measures

Because previous studies showed a possible impact of the virtual representation on performance [45], 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 [22]. We therefore included the maximum reach estimation task described in Section 4.3.2 after each main task, to evaluate whether the virtual representation would impact maximum reach perception.

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 [22]. 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 [7]. Therefore we propose as 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 [45], 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)**.

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

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 ($Mdn = 5$, $IQR = 3.438 - 5.812$) 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 ($Mdn = 3.75$, $IQR = 3 - 4.667$ for Ownership, $Mdn = 2.625$, $IQR = 1.75 - 3.406$ for Appearance, $Mdn = 3.42$, $IQR = 2.667 - 4.167$ for Multi-Sensory, $Mdn = 2.75$, $IQR = 2 - 3.833$ 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 ($W = 0.157$). Pairwise tests showed that the score for R - Ø 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 3.

For all components, we did not find any order effect.

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 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 *controllingTransparent*, 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

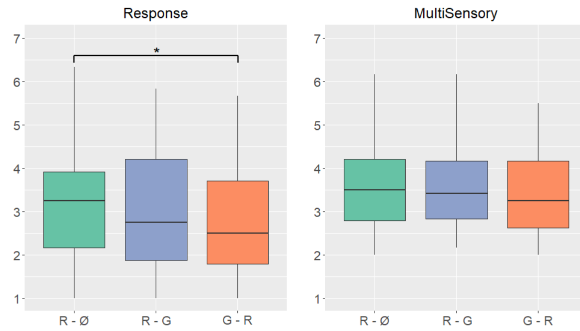

Fig. 3. Results for the two components Response and Multi-Sensory from the PGF questionnaire in Experiment 1, for which a main effect of *Representation* was found. Only the pairwise test on the Response component showed a significant difference between R - Ø and G - R ($p < 0.05$). There was no main effect for other components.

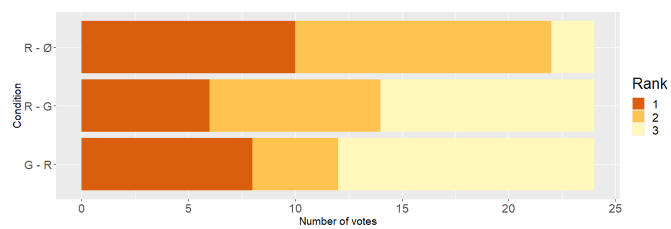

Fig. 4. Ranking for the different conditions in the Go-Go experiment. R - Ø was preferred with 10 participants ranking it as first.

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 ($p < 0.05$).

Preference R - Ø was the preferred condition, with 10 participants ranking it as their most preferred condition (see Figure 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* ($Mdn = 6$, $IQR = 6 - 7$).

4.7.2 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 - Ø, $89.9 \pm 16.9\%$ 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. There was a learning effect, with participants performing better at the end of the experiment than at the beginning. People took 105.7 ± 40.7 seconds in average in condition R - Ø, 96.6 ± 25.3 seconds in R - G and 99.3 ± 22.8 seconds in G - R.

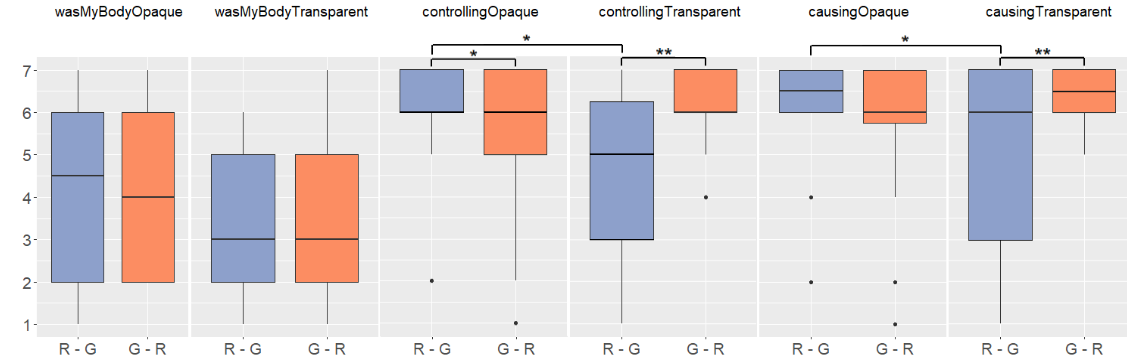

Fig. 5. Results of additional questions on the senses of ownership and agency for R - G and G - R in the experiment with the Go-Go technique. * $p < 0.05$, ** $p < 0.01$

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 - Ø 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. 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 than 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. These results seem to suggest that the interaction capabilities of the avatar play an important role on the sense of agency, and that the interaction capabilities of the avatar could compensate for deformations of the shape and the motions of the avatar.

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 [13, 28].

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 [13] 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.

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.

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.

5.2 PRISM Technique Implementation

The PRISM technique (see implementation in [15]) 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. Considering the chosen thresholds, and thanks to the instantaneous offset recovery when exceeding $MaxV$, the offsets stayed reasonable and the virtual hand could not drift away.

- $HandSpeed < MinV$. In this case, the motion is considered as noise and not intentional motion. We used $MinV = 0.01 m/s$ 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 $SC = 0.1 m/s$ for translation, and $SC = 50\, degree/s$ for rotation.
- $SC < HandSpeed < MaxV$. In this case we use a one-to-one mapping. We chose $MaxV = 0.2 m/s$ 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.

5.3 Task

The task was similar to the 6-DOF task considered by Frees et al. [15]. 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 1). When the object was correctly placed, it turned green. The global 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.

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 6). We added a fourth condition, Ø - 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.

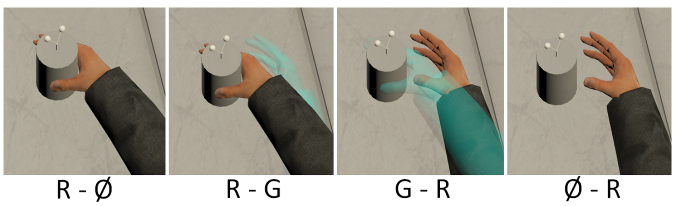

Fig. 6. Different levels of *Representation* in the second experiment with amplified motion. The interactive arm is either realistic (in R - Ø or R - G), transparent (in G - R) or not displayed (in Ø - R). A co-located arm is displayed, either a transparent one (in R - G) or a realistic one (in G - R and Ø - R).

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.

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.

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 [12]. 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)**.

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.

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 Ø - 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 7. Components scores were globally average ($Mdn = 3.833$, $IQR = 2.667-4.667$ for Ownership, $Mdn = 3.125$, $IQR = 2.125-3.5$ for Appearance, $Mdn = 3.5$, $IQR = 2.958-4.375$ for Multi-Sensory, $Mdn = 3$, $IQR = 2-3.667$ 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 - Ø 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 - Ø 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 - Ø 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 - Ø was significantly higher than in R - G ($p < 0.05$). There was no other significant difference.

For all components, we did not find any order effect.

Additional questions For the additional questions, we did not find any significant difference (see Figure 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*

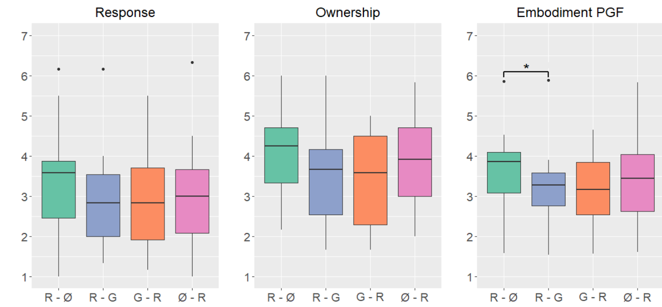

Fig. 7. Results for the two components Response and Ownership, as well as the global Embodiment score (from the PGF questionnaire) in Experiment 2, for which a main effect of *Representation* was found. Only the pairwise test on Embodiment scores showed a significant difference between R - Ø and R - G ($p < 0.05$). There was no main effect for other components.

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 - Ø was the preferred condition, with 13 participants ranking it as their most preferred condition (see Figure 9). Its average rank was 1.92. R - G came second with an average rank of 2.38, then Ø - R (2.58) and G - R (3.13) as the least preferred. 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* ($Mdn = 6$, $IQR = 5 - 7$).

5.7.2 Objective Measures

The number of completions was slightly higher in R - Ø but no significant difference was found between the four conditions ($F_{2.76,60.63} = 2.43$, $p = 0.079$, $\eta_p^2 = 0.100$). There was a learning effect, with participants performing better at the end of the experiment than at the beginning. People correctly placed 15.71 ± 4.91 objects in average in R - Ø, 13.38 ± 6.02 in G - R, 13.46 ± 5.08 in R - G and 13.33 ± 5.31 in Ø - 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 Ø - R than in R - Ø. The average number of adjustment releases was equal to 15.79 ± 7.04 in R - Ø, 16.42 ± 9.49 in G - R, 15.29 ± 7.77 in R - G and 19.71 ± 7.37 in Ø - R. Also, neither the offsets created nor the hand velocity were significantly different between the conditions. The average offset was $3.39 \pm 0.97cm$.

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 - Ø but pairwise tests could not show significant results. Only the global embodiment score showed that embodiment in R - Ø 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 - Ø, and equivalent for dual representations and the single representation Ø - R. The absence of a significant difference may be due to the number of participants. We also reported that the number of adjustment releases was high in Ø - 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 [4].

Also, the preference for condition R - Ø was clearer than in the first experiment. But interestingly, R - G was often ranked as 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 [15] where the virtual representation moves away from the object (like Ø - 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.

6 General Discussion

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

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, which is in line with previous studies [5, 30]. 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 [25, 34] or can embody an extended arm until a certain length [13, 22]. 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 - Ø). 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 [45], 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.

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

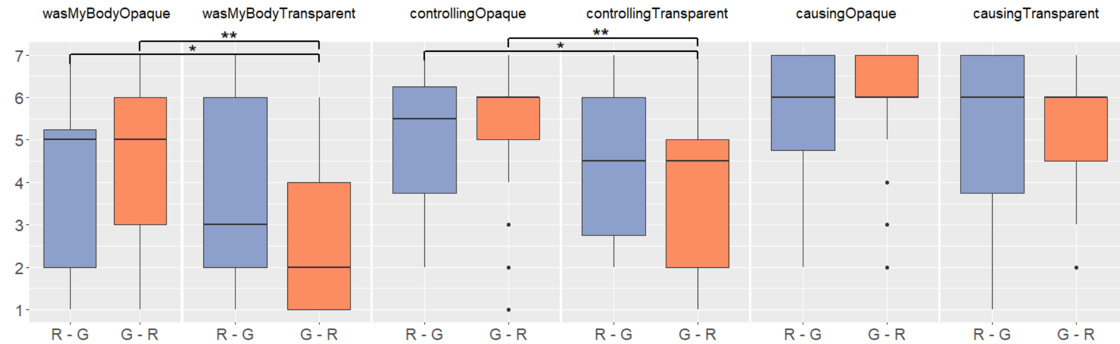

Fig. 8. Results of additional questions on the senses of ownership and agency for G - R and R - G in the experiment with the PRISM technique. * $p < 0.05$, ** $p < 0.01$

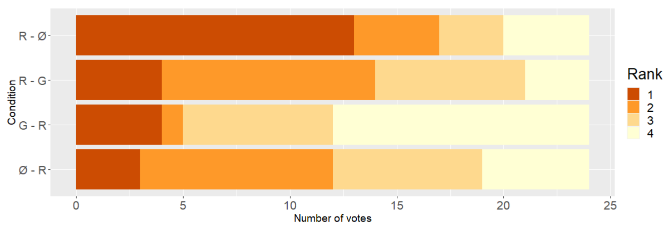

Fig. 9. Ranking for the different conditions in the PRISM experiment. R - Ø was preferred with 13 participants ranking it as first.

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.

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 [32, 38], 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 [40].

6.4 Limitations and Future Work

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 [4], 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 happen 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. Dual representations could also be studied when using haptic retargeting [1], but the results might be similar to the results in our experiment with PRISM as it usually does not create big offsets. 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. In this case, dual representations could be preferred by users as it would be more useful.

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. [30] could be called duplicated representations. We hope this work will steer new studies and open more questions on the topics of embodiment and control of multiple representations.

Acknowledgments

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References

[1] M. Azmandian, M. Hancock, H. Benko, E. Ofek, and A. D. Wilson. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, p. 1968–1979, 2016.

[2] M. Botvinick and J. Cohen. Rubber hands 'feel' touch that eyes see. *Nature*, 391(6669):756–756, 1998.

[3] E. Burns, S. Razzaque, A. T. Panter, M. C. Whitton, M. R. McCallus, and F. P. Brooks. The hand is slower than the eye: a quantitative exploration of visual dominance over proprioception. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pp. 3–10, 2005.

[4] R. Canales, A. Normoyle, Y. Sun, Y. Ye, M. D. Luca, and S. Jörg. Virtual grasping feedback and virtual hand ownership. In *ACM Symposium on Applied Perception 2019*, SAP '19, 2019.

[5] W.-Y. Chen, H.-C. Huang, Y.-T. Lee, and C. Liang. Body ownership and the four-hand illusion. *Scientific reports*, 8(1):1–17, 2018.

[6] W. Chinthammit, T. Merritt, S. Pedersen, A. Williams, D. Visentin, R. Rowe, and T. Furness. Ghostman: augmented reality application for telerehabilitation and remote instruction of a novel motor skill. *BioMed research international*, 2014.

[7] N. David, A. Newen, and K. Vogeley. The "sense of agency" and its underlying cognitive and neural mechanisms. *Consciousness and cognition*, 17(2):523–534, 2008.

[8] D. Dewez, L. Hoyet, A. Lécuyer, and F. A. Argelaguet Sanz. Towards "Avatar-Friendly" 3D Manipulation Techniques: Bridging the Gap Between Sense of Embodiment and Interaction in Virtual Reality. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–14, 2021.

[9] M. H. Draper, M. J. Wells, V. J. Gawron, and I. Tom A. Furness. Exploring the influence of a virtual body on spatial awareness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 40(22):1146–1150, 1996.

[10] H. H. Ehrsson. How many arms make a pair? Perceptual illusion of having an additional limb. *Perception*, 38(2):310–312, 2009.

[11] S. Esmaeili, B. Benda, and E. D. Ragan. Detection of scaled hand interactions in virtual reality: The effects of motion direction and task complexity. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 453–462. IEEE, 2020.

[12] C. Farrer, M. Bouchereau, M. Jeannerod, and N. Franck. Effect of distorted visual feedback on the sense of agency. *Behavioural neurology*, 19(1, 2):53–57, 2008.

[13] T. Feuchtner and J. Müller. Extending the body for interaction with reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, p. 5145–5157, 2017.

[14] T. Feuchtner and J. Müller. Ownershift: Facilitating overhead interaction in virtual reality with an ownership-preserving hand space shift. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, pp. 31–43, 2018.

[15] S. Frees, G. D. Kessler, and E. Kay. PRISM interaction for enhancing control in immersive virtual environments. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 14(1):2–es, 2007.

[16] A. Guterstam, D. E. Larsson, J. Szczotka, and H. H. Ehrsson. Duplication of the bodily self: a perceptual illusion of dual full-body ownership and dual self-location. *Royal Society open science*, 7(12):201911, 2020.

[17] P.-H. Han, K.-W. Chen, C.-H. Hsieh, Y.-J. Huang, and Y.-P. Hung. Ar-arm: Augmented visualization for guiding arm movement in the first-person perspective. In *Proceedings of the 7th Augmented Human International Conference 2016*, pp. 1–4, 2016.

[18] L. Heydrich, T. Dodds, J. Aspell, B. Herbelin, H. Buelthoff, B. Mohler, and O. Blanke. Visual capture and the experience of having two bodies–evidence from two different virtual reality techniques. *Frontiers in psychology*, 4:946, 2013.

[19] A. Kalckert and H. H. Ehrsson. The spatial distance rule in the moving and classical rubber hand illusions. *Consciousness and cognition*, 30:118–132, 2014.

[20] S. Kasahara, K. Konno, R. Owaki, T. Nishi, A. Takeshita, T. Ito, S. Kasuga, and J. Ushiba. Malleable embodiment: changing sense of embodiment by spatial-temporal deformation of virtual human body. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 6438–6448, 2017.

[21] K. Kilteni, R. Groten, and M. Slater. The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments*, 21(4):373–387, 2012.

[22] K. Kilteni, J.-M. Normand, M. V. Sanchez-Vives, and M. Slater. Extending body space in immersive virtual reality: A very long arm illusion. *PLOS ONE*, 7(7):1–15, 2012.

[23] M. Kocur, M. Kloss, V. Schwind, C. Wolff, and N. Henze. Flexing muscles in virtual reality: Effects of avatars' muscular appearance on physical performance. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, CHI PLAY '20, p. 193–205. Association for Computing Machinery, 2020. doi: 10.1145/3410404.3414261

[24] E. Kokkinara and M. Slater. Measuring the effects through time of the influence of visuomotor and visuotactile synchronous stimulation on a virtual body ownership illusion. *Perception*, 43(1):43–58, 2014.

[25] E. Kokkinara, M. Slater, and J. López-Moliner. The effects of visuomotor calibration to the perceived space and body, through embodiment in immersive virtual reality. *ACM Trans. Appl. Percept.*, 13(1), 2015.

[26] B. Laha, J. N. Bailenson, A. S. Won, and J. O. Bailey. Evaluating control schemes for the third arm of an avatar. *Presence: Teleoperators and Virtual Environments*, 25(2):129–147, 2016. doi: 10.1162/PRES_a_00251

[27] M. E. Latoschik, D. Roth, D. Gall, J. Achenbach, T. Waltemate, and M. Botsch. The effect of avatar realism in immersive social virtual realities. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, VRST '17. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3139131.3139156

[28] L. P. Lin, N. M. McLatchie, and S. A. Linkenauger. The influence of perceptual–motor variability on the perception of action boundaries for reaching. *Journal of Experimental Psychology: Human Perception and Performance*, 46(5):474, 2020.

[29] M. Martini, K. Kilteni, A. Maselli, and M. V. Sanchez-Vives. The body fades away: investigating the effects of transparency of an embodied virtual body on pain threshold and body ownership. *Scientific reports*, 5:13948, 2015.

[30] R. Miura, S. Kasahara, M. Kitazaki, A. Verhulst, M. Inami, and M. Sugimoto. Multisoma: Distributed embodiment with synchronized behavior and perception. In *Augmented Humans Conference 2021*, pp. 1–9, 2021.

[31] N. Ogawa, T. Narumi, and M. Hirose. Effect of avatar appearance on detection thresholds for remapped hand movements. *IEEE transactions on visualization and computer graphics*, 27(7):3182–3197, 2020.

[32] T. C. Peck and M. Gonzalez-Franco. Avatar embodiment. a standardized questionnaire. *Frontiers in Virtual Reality*, 1:44, 2021.

[33] T. C. Peck and A. Tutar. The impact of a self-avatar, hand collocation, and hand proximity on embodiment and stroop interference. *IEEE Transactions on Visualization and Computer Graphics*, 26(5):1964–1971, 2020. doi: 10.1109/TVCG.2020.2973061

[34] T. Porssut, B. Herbelin, and R. Boulic. Reconciling being in-control vs. being helped for the execution of complex movements in vr. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 529–537, 2019.

[35] I. Poupyrev, M. Billinghurst, S. Weghorst, and T. Ichikawa. The go-go interaction technique: non-linear mapping for direct manipulation in VR. In *Proceedings of the 9th annual ACM symposium on User interface software and technology*, pp. 79–80, 1996.

[36] M. Prachyabrued and C. W. Borst. Visual feedback for virtual grasping. In *2014 IEEE symposium on 3D user interfaces (3DUI)*, pp. 19–26. IEEE, 2014.

[37] N. Rosa, R. C. Veltkamp, W. Hürst, T. Nijboer, C. Gilbers, and P. Werkhoven. The supernumerary hand illusion in augmented reality. *ACM Transactions on Applied Perception (TAP)*, 16(2):1–20, 2019.

[38] D. Roth and M. E. Latoschik. Construction of the Virtual Embodiment Questionnaire (VEQ). *IEEE Transactions on Visualization and Computer Graphics*, 26(12):3546–3556, 2020. doi: 10.1109/TVCG.2020.3023603

[39] J. Schjerlund, K. Hornbæk, and J. Bergström. Ninja hands: Using many hands to improve target selection in vr. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–14, 2021.

[40] R. Skarbez, M. Whitton, and M. Smith. Mixed reality doesn't need standardized evaluation methods. In *CHI 2021 Workshop - Evaluating User Experiences in Mixed Reality*, 2021.

[41] M. Slater, D. Perez-Marcos, H. H. Ehrsson, and M. V. Sanchez-Vives. Towards a digital body: the virtual arm illusion. *Frontiers in human neuroscience*, 2:6, 2008.

[42] A. Steed, Y. Pan, F. Zisch, and W. Steptoe. The impact of a self-avatar on cognitive load in immersive virtual reality. In *2016 IEEE Virtual Reality (VR)*, pp. 67–76, 2016. doi: 10.1109/VR.2016.7504689

[43] W. Steptoe, A. Steed, and M. Slater. Human tails: Ownership and control

of extended humanoid avatars. *IEEE transactions on visualization and computer graphics*, 19:583–90, 2013.

[44] Y. Tian, Y. Bai, S. Zhao, C.-W. Fu, T. Yang, and P. A. Heng. Virtually-extended proprioception: Providing spatial reference in vr through an appended virtual limb. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2020.

[45] T. Q. Tran, H. Shin, W. Stuerzlinger, and J. Han. Effects of virtual arm representations on interaction in virtual environments. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, VRST '17, 2017.

[46] U. Yang and G. J. Kim. Implementation and Evaluation of "Just Follow Me": An Immersive, VR-Based, Motion-Training System. *Presence: Teleoperators & Virtual Environments*, 11(3):304–323, 2002.

[47] Y. Yuan and A. Steed. Is the rubber hand illusion induced by immersive virtual reality? In *2010 IEEE Virtual Reality Conference (VR)*, pp. 95–102. IEEE, 2010.