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Quantitative and Qualitative Exploration of the Effect of a Wearable Item on Non-Organic Virtual Limb Embodiment and User Behavior in Immersive Environments

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Abstract

This experiment was designed to investigate the potential contribution to the sense of embodiment of a wristband worn by the participants in both real and virtual environments. In addition, two virtual limb models were compared following a mixed between-within subjects design: an organic hand and a non-organic prosthesis matching the proposed task. Quantitative results revealed no significant effect of the wristband, while post-experiment semistructured interviews revealed that the wristband fostered the identification with the virtual limbs for several participants, but that it might be conditioned by interindividual differences. Ownership scores were significantly higher with the virtual hand. However, participants experienced a very high sense of agency with both conditions despite the lack of finger tracking when controlling the prosthesis. Agency was positively correlated with participants' perceived change in their body schema when embodying the prosthesis. Subjective and objective measures demonstrated that participants were less hesitant and that more collisions were recorded at higher speeds against potentially threatening objects with the non-organic prosthesis.

1 Introduction

Virtual reality (VR) and body-tracking technologies allow the substitution of one's own body with alternative virtual representations. Multisensory integration makes it possible to embody virtual characters presenting, to some extent, dissimilarities with users' body schema (Laha et al., 2016; Steptoe et al., 2013). Indeed, previous research demonstrated the ability of participants to feel a sense of ownership over virtual bodies with different morphological characteristics thanks to bottom-up factors such as visuomotor or visuotactile synchrony (Hoyet et al., 2016). In this context, we designed an experiment to investigate if top-down factors could also favor the embodiment of alternative virtual limbs. We developed a VR application aiming at studying the potential contribution of the reproduction of a real wearable item on the sense of embodiment

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Figure 1. *Non-organic hammer prosthesis and organic hand with the wristband in the virtual environment of the experiment.*

over a dissimilar virtual limb (see Figure 1). We reproduced a wristband that was displayed in the virtual environment on an arm prosthesis that does not present a human body schema. We wanted to avoid inducing a sense of embodiment thanks to the movement synchronization of virtual fingers. The goal of this experiment was to investigate whether the perception and the matching between the real item worn by participants and its reproduction in the virtual environment could favor the induction of a sense of ownership over a non-organic limb. The sense of embodiment can be subject to interindividual differences and may vary from one participant to another depending on several factors (Maselli & Slater, 2013). With this experiment, we wanted to explore a simple way to reduce the gap between users. If we expected some participants to be able to embody the non-organic arm without any addition to the limb, we wanted to investigate the potential contribution of the real item reproduction for the most reluctant ones. Thus, this study was designed to potentially provide developers with a convenient, scalable, and affordable way to improve and push back the boundaries of embodiment in VR applications.

The next section presents a state of the art on the sense of embodiment in VR and especially on previous research focusing on users' ability to embody dissimilar virtual limbs. Section 3 presents the design of the experiment and its protocol. Results are analyzed in Section 4 and discussed in Section 5. Limits are highlighted in Section 6 along with our potential future work. Section 7 presents the conclusion of the study.

2 Related Work

2.1 Embodiment in Virtual Environments

The sense of embodiment in virtual environments refers to the illusion of being located inside, of owning and controlling the body of a virtual character. It was defined by Kilteni et al. (2012) as the sense that emerges when the properties of a virtual body are processed as if they were the properties of one's own biological body.

Originally, the rubber hand illusion (RHI) paradigm demonstrated that it was possible to bias subjects' body perception with synchronous visuotactile stimulation over a rubber hand inducing a proprioceptive drift, that is to say, a mislocalization of the real hand, as well as a sense of ownership over the fake hand (Botvinick & Cohen, 1998). This paradigm translates well in virtual environments where similar outcomes can be observed over virtual limbs (Sanchez-Vives et al., 2010; Slater et al., 2008). Nowadays, VR technologies, such as head-mounted displays and motion capture suits, allow the embodiment and control of virtual characters (avatars) in real time (Spanlang et al., 2014). Embodying avatars in immersive virtual environments can affect both user behavior (Banakou et al., 2013; Gorisse et al., 2019; Kilteni et al., 2013; Yee et al., 2009) and cognition (Banakou et al., 2018; Kocur et al., 2020; Slater et al., 2019). It is therefore particularly important for researchers to understand the underlying mechanisms and outcomes of embodiment in virtual environments to get the most out of it. It is now commonly accepted that embodiment relies on three main factors (Kilteni et al., 2012):

- **Self-location**, which corresponds to the volume in space where users feel located. The sense of self-location in immersive virtual environments is mainly impacted by the viewpoint (e.g., first- or third-person perspective) (Debarba et al., 2017; Fribourg et al., 2020; Gorisse et al., 2017) and visuotactile stimulation inducing a proprioceptive drift (Botvinick & Cohen, 1998; Ehrsson, 2007; Lenggenhager et al., 2007);
- **Agency**, defined by Blanke and Metzinger (2009) as the “global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will.” Visuomotor synchrony between users and their avatars is a very effective contributor to the sense of agency (Caspar et al., 2015; Jeunet et al., 2018). Agency can also vary depending on interindividual differences, as demonstrated by the experiment of Dewez et al. (2019) where a correlation was observed with participants’ internal locus of control; and
- **Body ownership**, which refers to one’s self-attribution of a body (Kilteni et al., 2012). Both visuotactile and visuomotor synchronization can induce the illusion of owning a virtual body (Bovet et al., 2018; Kokkinara & Slater, 2014; Slater et al., 2009) if it is acknowledged that multisensory integration contributes greatly to the sense of body ownership. Nonetheless, other factors, such as the degree of similarity with the virtual body, can affect the illusion of owning a virtual body (Gorisse et al., 2019; Latoschik et al., 2017; Waltemate et al., 2018) or a virtual hand (Argelaguet et al., 2016; Lin & Jörg, 2016).

Considering the goal of the experiment reported in this paper, we won’t focus on self-location as, according to the aforementioned research, none of our experimental conditions can impact the perceived location of the participants. However, the morphological properties of the virtual limb and the reproduction of a real wristband worn by the participants could affect both their sense of agency and their sense of body ownership.

Bottom-up factors, such as visuotactile (Kokkinara & Slater, 2014; Maselli & Slater, 2013; Normand et al., 2011) or visuomotor synchrony (Kokkinara & Slater, 2014; Sanchez-Vives et al., 2010), are critical contributors to the sense of embodiment in virtual environments. Indeed, previous research demonstrated that it was possible to embody virtual characters presenting various demographic characteristics (Kilteni et al., 2013; Peck et al., 2013) and morphological properties (Banakou et al., 2013; Normand et al., 2011). This is of particular importance, as the experiment reported in this paper compared virtual limbs presenting different morphologies. However, a lower level of agency was expected due to the lack of visuomotor synchronization (no finger tracking) in one of our experimental conditions. The link between virtual characters’ anthropomorphism level and embodiment will be addressed in the following section.

Regarding top-down factors, we mentioned that the similarity between users’ appearance and their avatar can impact their sense of body ownership (Fribourg et al., 2020; Gorisse et al., 2019; Waltemate et al., 2018). While the effect size is generally smaller than multisensory integration, it could be used as a way to improve embodiment in virtual environments. Following this principle of self-identification with virtual characters, we wanted to investigate if the reproduction of a real wristband worn by the participants could improve the identification with virtual limbs presenting non-anthropomorphic physical properties.

2.2 Anthropomorphism, Body Schema, and Embodiment

Visual fidelity of virtual characters can be divided into three categories (Garau, 2003):

- **Anthropomorphism** (*non-humanoid* ↔ *humanoid*): morphological characteristics of the virtual character (Dubosc et al., 2021; Lugrin et al., 2015; Nowak & Biocca, 2003).

- **Realism** (*cartoonish ↔ photorealistic*): level of detail of the mesh and textures of the 3D model (Zell et al., 2015; Zibrek et al., 2019).
- **Truthfulness** (*does not look like the user ↔ looks like the user*): degree of similarity between the user and the virtual character (Benford et al., 1997; Gorisse et al., 2018, 2019; Waltemate et al., 2018).

In the frame of this study, we will focus mainly on the impact of anthropomorphism and realism on the sense of embodiment in immersive virtual environments. Nevertheless, while not being mandatory when relying on congruent multisensory integration, truthfulness can also improve the sense of embodiment when controlling lookalike virtual characters (Gorisse et al., 2019; Waltemate et al., 2018).

Previous experiments demonstrated that it is possible to embody nonrealistic virtual hands (Argelaguet et al., 2016; Lin & Jörg, 2016). In their experiment, Argelaguet et al. (2016) observed a higher sense of ownership over realistic hands. They argued that a direct mapping between the degrees of freedom of the real and the virtual hand led to a higher sense of ownership over the virtual limb. However, unlike the study of Lin and Jörg (2016), they observed a higher sense of agency with more abstract virtual hands as soon as the system provides an efficient level of control. In their experiments, Lin and Jörg (2016) observed a high sense of ownership over non-realistic virtual hands (e.g., cartoony, robot, zombie, etc.). It should be noted that they also recorded a high variability between the participants. However, nonanthropomorphic hands (wooden block) led to a significantly lower sense of ownership, which is in line with the results of Pyasik et al. (2020).

While the aforementioned studies demonstrated that a sense of body ownership can be induced over nonrealistic virtual hands using congruent visuomotor or visuotactile stimulation, they also observed that nonanthropomorphic hands led to a lower sense of ownership. However, some research around the concept of homuncular flexibility (Won et al., 2015) demonstrated that it is possible to embody and control virtual characters presenting a non-humanoid body schema. For instance, the experiment of Steptoe et al. (2013) demonstrated that participants were able to feel a sense of ownership over an avatar with a tail and that they were more involved in avoiding virtual threats to both the tail and the body. Laha et al. (2016) and Hoyet et al. (2016) investigated the impact of controlling a body with three arms or six fingers on the sense of body ownership. In both experiments, participants learned the control schemes and were able to feel a sense of ownership and to interact with the additional limbs. These experiments highlight users' potential to embody virtual bodies with morphological differences.

To summarize, on the one hand, previous studies tend to demonstrate that it might not be possible to embody virtual limbs presenting a minimalist and nonanthropomorphic body schema, such as a virtual wooden block, under both limited visuomotor synchronization (no fingers) (Lin & Jörg, 2016) and congruent visuotactile stimulation (Pyasik et al., 2020). On the other hand, extended virtual bodies presenting additional limbs could be embodied using ad hoc control schemes (Hoyet et al., 2016; Laha et al., 2016). Moreover, it should be noted that Cardinali et al. (2021) recently demonstrated that a mechanical grabber barely resembling a hand can induce a sense of body ownership, a phenomenon named "toolish hand illusion" by the authors. This experiment did not rely on virtual environments and was adapted from the RHI paradigm.

In this context, we designed an experiment to further investigate users' capacity to embody a virtual limb that does not present an anthropomorphic body schema limiting in return the contribution of synchronous finger movements to the sense of embodiment. As mentioned above, this experiment was also designed to analyze the potential top-down benefits of the virtual reproduction of a wristband worn by the participants in the real world to favor their identification with the nonanthropomorphic virtual limb.

3 Materials and Methods

3.1 Task and Conditions

For this experiment, we developed a VR application derived from the famous Whac-A-Mole arcade

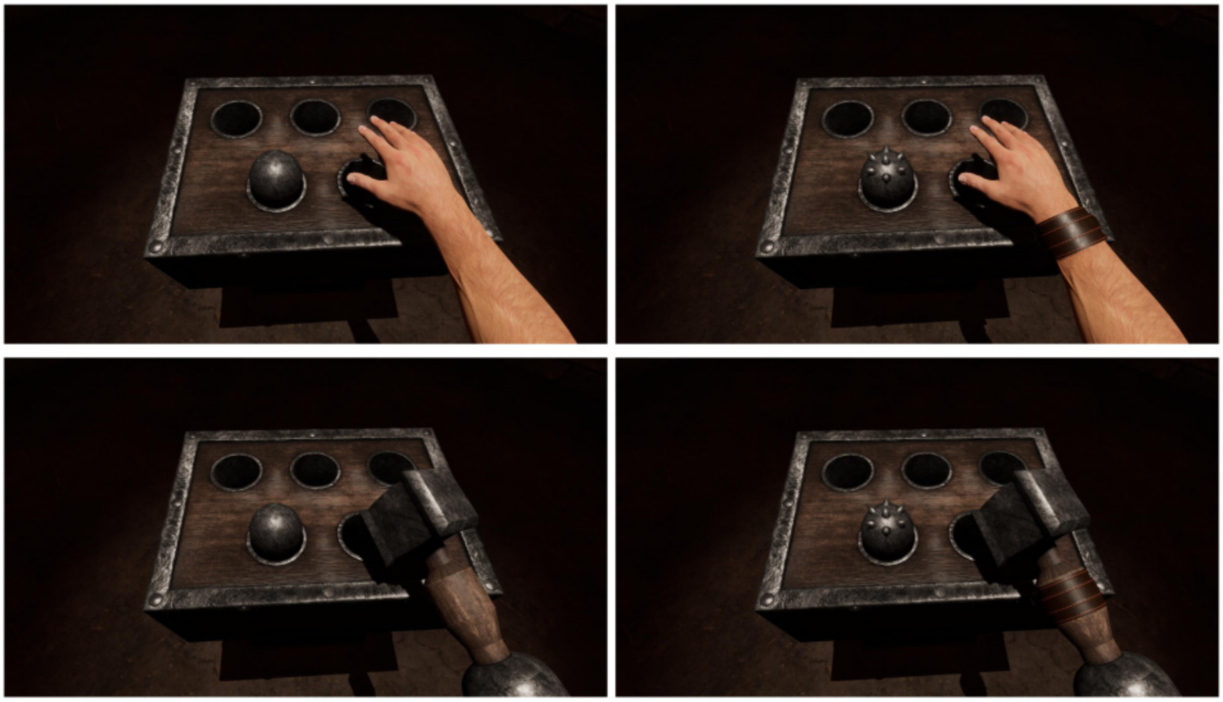


Figure 2. *Screenshots of the experimental conditions: hand (HD) and hand wristband (HDW) (top), hammer (HR) and hammer wristband (HRW) (bottom). The normal mole (left) and a mole with spikes (right) can be seen on the game board.*

game (see Figure 2). This type of game allows users to remain engaged in the task throughout the experiment. The benefit of this task is twofold. First, it allows the participant's hand to be kept in the field of view of the VR headset in order to maximize the attention paid to the virtual limb. Furthermore, keeping the hand in the field of view of the headset, and thus in the field of view of the tracking device, limits occlusion and tracking issues. Second, in addition to visuomotor synchronization, another sensory stimulation is induced by the actual table (see Figure 3) that provides a passive haptic feedback when the participants hit the virtual objects with the hand.

The game we developed requires the participants to hit 50 objects appearing successively and one at a time. To obtain additional behavioral data related to the sense of embodiment, the object to be hit is occasionally replaced by a potentially dangerous one (spikes) in order to measure avoidance behaviors and speed profiles (Argelaguet et al., 2016; Fribourg et al., 2021).

Figure 3. *Participant immersed in the virtual environment with the HTC Vive Pro VR headset, the leap motion, and the wristband.*

Table 1. *Experimental Conditions Summary*

	No wristband	Wristband
Hand	Group 1 (HD)	Group 2 (HDW)
Hammer prosthesis	Group 1 (HR)	Group 2 (HRW)

We used four conditions in this experiment following a 2 × 2 mixed factorial design. We compared two anthropomorphism levels with distinct limb models (hand versus hammer prosthesis) and the effect of the addition of a real wristband and its virtual counterpart on the participant's arm (see Table 1 for an overview of the conditions of the experiment). A couple of alternative items could have been considered for this experiment, including rings and gloves, but it would have been complicated to match participants' morphology, as well as the 3D model of the virtual prosthesis.

As opposed to the experiment of Bartl et al. (2021), the wristband was worn by the participants in both the real and the virtual environments. Each group of participants tested the two models following a within-subject design (see Table 1). The first model was a realistic gender- and color-matched hand. Despite the fact that sensory motor contingencies allow us to embody virtual characters with different body characteristics, we wanted to avoid any gender side effect (Schwind et al., 2017) or any delay in the "incorporation" process induced by the skin color in mismatching configurations (Lira et al., 2017). The second arm was a hammer prosthesis relevant for the proposed task. This prosthesis followed the participant's arm movements including the forearm twist to rotate the hammer. No other wrist rotation and finger movements were considered in this condition. These models were presented in a counterbalanced order. However, only one group tested these models with the addition of the wristband.

3.2 Virtual Environment

The VR application was developed with the 2019.4 LTS version of the Unity 3D engine. The environment is relatively simple, yet consistent with the wristband and the limb models we selected. It was designed to keep the participant focused on the task while being plausible and coherent. It is composed of a relatively dark room with a skylight well over the game board. This configuration ensures proper lighting of the participant's virtual limb and of the interactive objects.

The game board is composed of five holes where the moles appear randomly. It is calibrated at the beginning of the VR exposure to fit with the real table. This process ensures that the participant's hand collides with the table when they hit the objects to provide a passive haptic feedback. We designed two types of moles for the task. The first one is a smooth and harmless object that must be hit by the participants. The second one is based on the same model but has additional spikes on top (see Figure 2). This model was designed to induce behavioral responses that can be recorded during the experiment, providing additional clues regarding the participant's sense of body ownership over the virtual limbs.

3.3 Apparatus

3.3.1 Virtual Reality Devices. The VR headset HTC Vive Pro was used to immerse the participants in the virtual environment with a resolution of 2880 × 1600 pixels (1440 × 1600 per eye) and a horizontal field of view of 110° at a refresh rate of 90 Hz. A leap motion was attached to the virtual reality headset to control both the virtual hand and the hammer prosthesis. This sensor has a refresh rate of 120 Hz and a field of view of 150° × 120° (see Figure 3). It should be noted that the participants performed the task using their dominant hand; the other option was disabled at the beginning of the experiment during the configuration of the application.

3.3.2 Wristband. We chose a wristband that fits the environment that we developed for the task. We wanted something that could adapt to every forearm shape regardless of the participant's gender. The wristband is large enough to be easily noticeable both in the real and in the virtual world. We recreated the 3D model as accurately as possible using Autodesk 3ds Max and Adobe Substance Painter softwares. The 3D model was rigged and skinned to be adjusted on the female and male arms, as well as on the hammer prosthesis (see Figures 2 and 3).

3.4 Participants

Forty participants (22 women and 18 men) aged from 15 to 53 ($M = 26.1$, $SD = 6.84$) were recruited for the experiment. Participants were divided into two groups (20 participants per group) to match the 2 × 2 mixed factorial design of the experiment (see Table 1). Each subject had correct or corrected vision. Each participant had at least one prior experience with immersive VR, and 28 of the participants play video games at least one hour a week. Seventeen participants were used to wearing a wristband or a watch near their dominant hand.

3.5 Procedure and Measures

Before starting the experiment, participants signed an information sheet and a consent form. Depending on their group (see Table 1), the wristband was put on the participant's dominant arm to ensure they got used to it before entering the virtual environment. They completed a pre-experiment questionnaire to collect their demographic information and their self-reported video game and virtual reality experiences. Participants were asked to sit on a chair facing a table. They were given the necessary instructions to enter the virtual environment. They were equipped with the VR headset. Depending on the experimental condition, the experimenter had to configure the application using a dedicated graphic interface to set the condition being tested, including the morphological properties (gender), skin color, and the activation of the virtual wristband.

At the beginning of each immersion session in the virtual environment, participants were invited to observe the virtual room in which they were located and to get used to their virtual limb (hand or hammer prosthesis) and the wristband, depending on their group. It was important to ensure that the participants noticed the wristband, especially on the hammer and on dark-skinned hands. Then, they had to perform the task consisting of hitting the objects appearing on the game board, while avoiding the objects presenting a potential danger (spikes). The avoidance instruction was not explicit in order to observe and record participants' instinctive reactions. They had 50 trials, including 5 trials with dangerous objects appearing at trials 11, 20, 33, 40, and 48. Participants' hand velocity and distance from the moles were recorded, as well as the number of collisions with the spikes.

After the first and the second immersion session in the virtual environment, participants had to complete a post-experiment questionnaire to assess their sense of body ownership, their sense of agency, and the perceived change in their body schema based on the virtual embodiment questionnaire (VEQ) (Roth & Latoschik, 2020) (see Table 2). We also included some items adapted from Gonzalez-Franco and Peck's (2018) questionnaire to assess participants' response to external stimuli, as there is no equivalent in the VEQ. Such items are relevant in the frame of our experiment, considering the virtual threat induced by the spikes. Items ranged from 1 to 7, and an average score for each subscale was calculated before the analysis.

After the second session, the experimenter conducted a semistructured interview with the participants to discuss their virtual limb, the potential impact of the wristband, and their reactions when facing the dangerous objects (see Table 3). In this context, it was necessary that participants experienced both the virtual hand and the hammer prosthesis to be able to compare the models and provide us with subjective qualitative feedback that we compared to objective data recorded during the experiment.

3.6 Hypotheses

- H1: Using a realistic color- and gender-matched virtual hand induces a higher sense of ownership (H1.1) and agency (H1.2) than controlling highly dissimilar virtual limbs (non-organic appearance).
- H2: Reproduction of a real item (wristband) worn by users in virtual environments improves the identification and the sense of ownership over highly dissimilar virtual limbs.
- H3: Controlling highly dissimilar virtual limbs induces a greater perception of change in the body schema.
- H4: Controlling highly dissimilar and non-organic virtual limbs reduces users' apprehension of potential virtual threats.

Table 2. *Ownership, Agency, Perceived Change, and Response to External Stimuli Questionnaire. Items Range from 1 to 7*

Body ownership
It felt like the virtual hand/hammer was my hand. It felt like the virtual hand/hammer parts were my hand parts. It felt like the virtual hand/hammer belonged to me.
Agency
The movements of the virtual hand/hammer felt like they were my movements. I felt like I was controlling the movements of the virtual hand/hammer. It felt like I was causing the movements of the virtual hand/hammer. The movements of the virtual hand/hammer were in sync with my own movements.
Perceived change in the body schema
I felt like the form or appearance of my own body had changed. I felt like the weight of my own body had changed.
Response to external stimuli (Threat)
I felt that my own hand could be affected by the dangerous object. When the dangerous object appeared, I felt the instinct to hold my hand. I had the feeling that I might be harmed by the dangerous object.

Table 3. *Post-Experiment Semistructured Interview*

Question list
How did it feel to control the hand/hammer in the virtual environment? Did the presence of the wristband impact your experience? How did you feel about the dangerous objects?

4 Results

Data were tested for normality and the Shapiro-Wilk Test revealed that some variables were not normally distributed ($p < .05$). However, considering that the Levene's test for equality of variances revealed no significant difference across the groups, we used mixed between-within subjects analyses of variance. Differences are considered significant when $p < .05$.

4.1 Embodiment

4.1.1 Quantitative Analysis. A mixed between-within subjects analysis of variance was conducted to assess the impact of the wristband on participants' sense of

Table 4. *Statistical Summary of the Answers to the Post-Experiment Questionnaire (Ownership, Agency, Perceived Change, and Threat) and of the Number of Collisions with Dangerous Objects (Spikes)*

	No wristband		Wristband	
	$\bar{x}$	σ	$\bar{x}$	σ
Ownership HD	5.10	0.41	5.51	0.31
Ownership HR	4.12	0.36	4.05	0.36
Agency HD	6.36	0.12	6.16	0.16
Agency HR	6.04	0.28	6.06	0.18
Change HD	3.10	0.35	2.55	0.30
Change HR	3.95	0.44	3.50	0.39
Threat HD	4.40	0.43	3.93	0.40
Threat HR	2.98	0.38	2.73	0.43
Collisions HD	3.15	2.06	3.35	2.16
Collisions HR	3.25	2.09	3.97	1.90

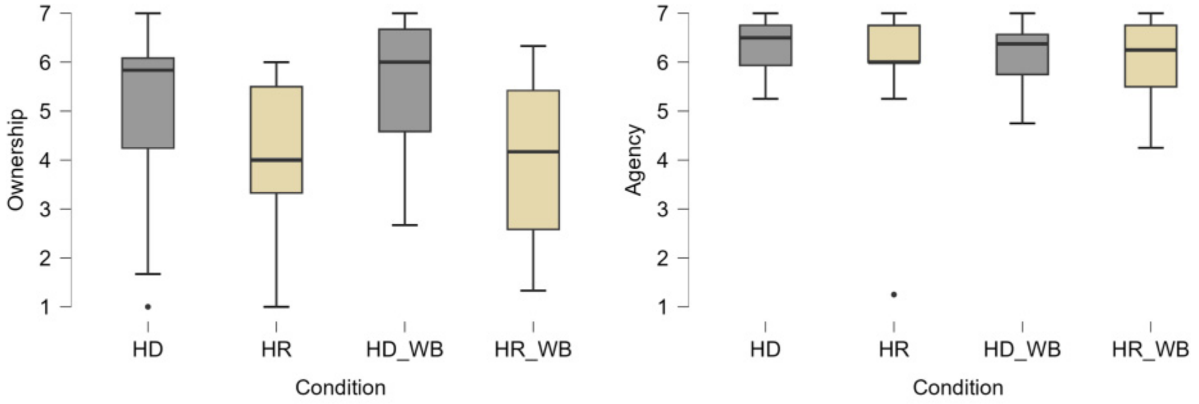
Mean and standard deviation are provided for each between subjects condition (no wristband and wristband) and within subjects condition (hand [HD] and hammer [HR]).

ownership over the virtual limb models (hand and hammer). There was no significant interaction between the wristband conditions and the models, $F(1, 38) = .559$, $p = .459$, partial eta squared = .014. There was a substantial main effect of the model, $F(1, 38) = 14.358$, $p = .001$, partial eta squared = .274, with both groups showing a higher sense of body ownership with the virtual hand (see Table 4 and Figure 4a). The main effect between the wristband conditions did not reach statistical significance, $F(1, 38) = .188$, $p = .667$, partial eta squared = .005.

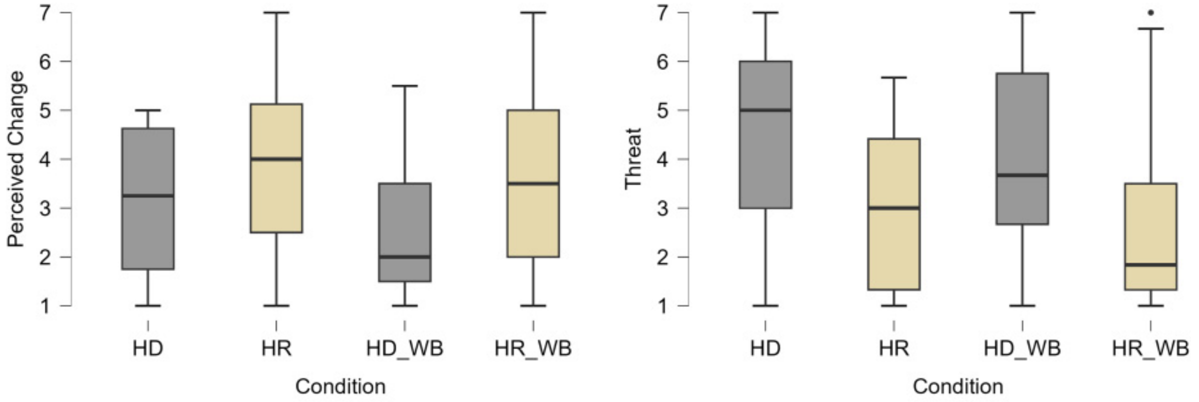
Another mixed between-within subjects analysis of variance was conducted to assess the impact of the wristband on participants' sense of agency with the virtual limb models (hand and hammer). There was no significant interaction between the wristband conditions and the models, $F(1, 38) = .509$, $p = .480$, partial eta squared = .013. There was no main effect of the model (Table 4 and Figure 4b), $F(1, 38) = 1.815$, $p = .186$, partial eta squared = .046. The main effect between the wristband conditions did not reach statistical significance, $F(1, 38) = .154$, $p = .697$, partial eta squared = .004.

Finally, a mixed between-within subjects analysis of variance was conducted to assess the impact of the wristband on participants' perceived change in their body schema with the virtual limb models (hand and hammer). There was no significant interaction between the wristband conditions and the models, $F(1, 38) = .033$, $p = .857$, partial eta squared = .001. There was a substantial main effect of the model, $F(1, 38) = 10.706$, $p = .002$, partial eta squared = .220, with both groups showing a higher perceived change with the hammer (Table 4 and Figure 4c). The main effect between the wristband conditions did not reach statistical significance, $F(1, 38) = 1.240$, $p = .272$, partial eta squared = .032.

4.1.2 Qualitative Analysis. The semistructured interviews carried out after both exposures to the virtual environment provided us with interesting insights to interpret the embodiment measures. The sense of body



[a] Ownership boxplot [b] Agency boxplot



[c] Perceived Change boxplot [d] Threat boxplot

Figure 4. *Ownership, agency, perceived change, and threat boxplots for hand (HD) and hammer (HR) with (WB) and without wristband.*

ownership was significantly higher with the virtual hand (Table 4 and Figure 4a), and this was acknowledged by over a quarter of the panel who explicitly mentioned the fact that the hand was very realistic and similar to their real hands:

- *Regarding the hand, WOW the visual is very confusing! I felt like it was my own hand. It was really detailed.*
- *I really thought it was mine. The hairiness was well done, it's crazy it looks like mine!*

Therefore, the level of detail of the virtual hands may have contributed to participants' sense of body ownership (along with multisensory integration), but according to some participants the realism level might be a double-edged sword. Indeed, 11 participants stated that the morphology was different (e.g., palm, fingers) and 8 participants perceived minor differences (e.g., nails, veins, hairiness) leading them to conclude that it was not their hand:

- *At the beginning of the experiment, I noticed that it was not my hand, I don't have such thin fingers and long nails.*
- *The fact that the hand was realistic, but different from mine was almost more disturbing than the hammer.*

Realism might be detrimental to the sense of embodiment in some contexts, especially when using virtual limbs quite similar to the participants' own limbs but with noticeable minor differences, an observation somewhat related to the uncanny valley phenomenon we will discuss further in the next section. It is also worth noting that 9 participants explained that they tried to conform their hand to the appearance of the hammer by closing their fist.

When it comes to the contribution of the wristband, qualitative results contrast with the post-experiment questionnaire. No interaction effect, nor main effect, of the wristband was observed. However, 8 participants out of the 20 (HDW and HRW conditions, Table 1) stated that it helped to favor the identification with the virtual hand, and 6 participants stated the same for the hammer prosthesis:

- *Putting the wristband before the experiment and finding it in the universe immediately made the virtual hand my own!*
- *The wristband brings credibility with the hand, but also with the hammer. We have a visual cue. The fact of seeing it and the feeling of wearing create a link.*
- *That's what made me really believe it was my hand (virtual hand and hammer).*

The wristband may have helped some participants to embody both the hand and the hammer. However, despite the embodiment phase consisting in observing and moving the virtual limb, 4 participants did not notice it on the virtual hand and 6 on the hammer prosthesis. Finally, 4 participants did not perceive any noticeable contribution. None of the collected demographic data revealed significant differences considering the inter-individual variability of the panel (gender or habit of wearing a wristband near their dominant hand) to explain such results.

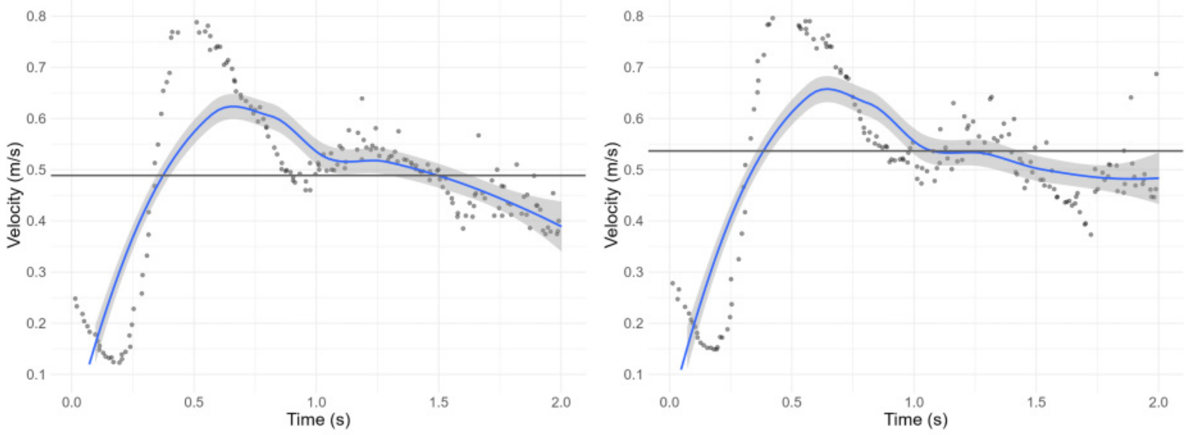
4.2 Response to Virtual Threats

4.2.1 Quantitative Analysis. A mixed between-within subjects analysis of variance was conducted to assess the impact of the wristband on the perception of the virtual threat with the virtual limb models (hand and hammer). There was no significant interaction between the wristband conditions and the models, $F(1, 38) = .101$, $p = .753$, partial eta squared = .003. There was a substantial main effect of the model, $F(1, 38) = 14.685$, $p < .001$, partial eta squared = .279, with both groups perceiving the virtual threat as more dangerous with the virtual hand (see Table 4 and Figure 4d). The main effect between the wristband conditions did not reach statistical significance, $F(1, 38) = .572$, $p = .454$, partial eta squared = .015.

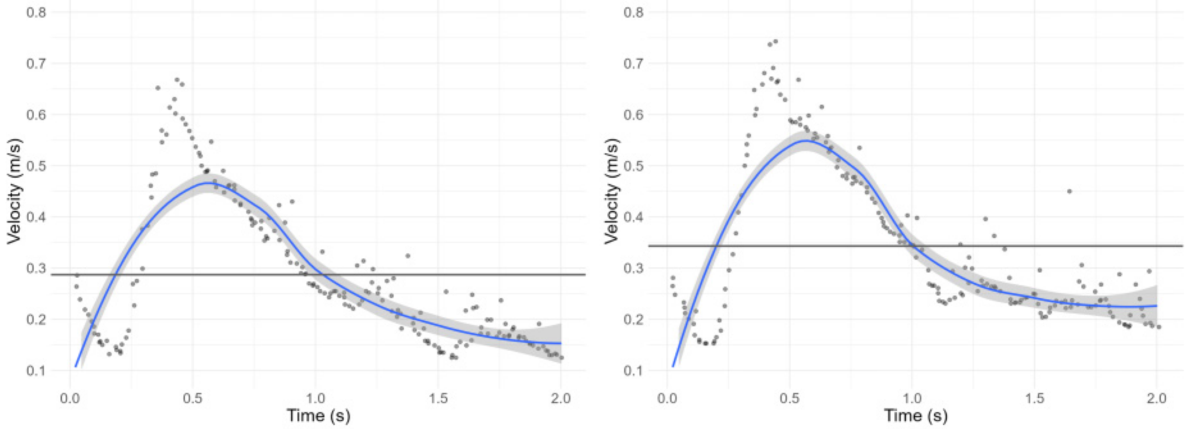
Regarding the recorded behavioral data, a mixed between-within subjects analysis of variance was conducted to assess the impact of the wristband on the number of collisions with the dangerous objects (spikes) with both the hand and the hammer. There was no significant interaction between the wristband conditions and the models, $F(1, 38) = .010$, $p = .920$, partial eta squared < .001. There was a substantial main effect of the model, $F(1, 38) = 8.689$, $p = .005$, partial eta squared = .186, with both groups having hit more dangerous objects with the hammer (see Table 4). The main effect between the wristband conditions did not reach statistical significance, $F(1, 38) = .088$, $p = .768$, partial eta squared = .002.

We also performed mixed between-within subjects analyses of variance to compare average velocities considering a two-second time frame. No interaction effects were observed. However, main effects revealed that velocities were lower for hazardous trials compared to normal trials with both the hand (see Figures 5a and 5c), $F(1, 38) = 85.254$, $p < .001$, partial eta squared = .692, and the hammer (see Figures 5b and 5d), $F(1, 38) = 43.552$, $p < .001$, partial eta squared = .534. Additionally, average velocities were higher with the hammer compared to the hand in both normal trials, $F(1, 38) = 7.333$, $p < .010$, partial eta squared = .162, and hazardous trials, $F(1, 38) = 12.445$, $p < .001$, partial eta squared = .247. The main effects between the wristband conditions did not reach statistical significance.

Comparing average velocities for each hazardous trial except for trial 11 (i.e., trials 20, 33, 40, and 48), we recorded several medium to large main effects with higher velocities for the hammer model at trial 20: $F(1, 38) = 8.653$, $p = .006$, partial eta squared = .185; trial 33: $F(1, 38) = 4.829$, $p = .034$, partial eta squared = .113; trial 40: $F(1, 38) = 6.209$, $p = .017$,



[a] Average hand velocity for normal trials. [b] Average hammer velocity for normal trials.



[c] Average hand velocity for hazardous trials. [d] Average hammer velocity for hazardous trials.

Figure 5. *Average velocities of the organic hand (left) and the hammer prosthesis (right) for both the normal (top) and hazardous (bottom) trials. Dark grey horizontal lines indicate mean values.*

partial eta squared = .140; trial 48: $F(1, 38) = 6.658$, $p = .014$, partial eta squared = .149.

In addition to average velocities, we processed max velocities and times of first velocity peaks in hazardous trials. Mixed between-within subjects analyses of variance revealed no interaction effects between the wristband conditions and the models. Marginally, a shorter time of first peak was recorded in favor of the hand at trial 20: $F(1, 38) = 5.571$, $p = .023$, partial eta squared = .128. Results also indicated two main effects in terms of max velocity in favor of the hammer prosthesis at trial 40: $F(1, 38) = 4.150$, $p = .001$, partial eta squared = .098 and 48: $F(1, 38) = 6.652$, $p = .014$, partial eta squared = .149. The main effects between the wristband conditions did not reach statistical significance.

4.2.2 Qualitative Analysis. Both subjective quantitative and objectives measures revealed significant differences between the hand and the hammer prosthesis models when it comes to participants' responses to virtual threats. Participants hit more dangerous objects at higher speed with the hammer model. Semistructured interviews are in line with these results. Only 7 participants mentioned not having perceived any difference between the models. Twenty-seven participants explained that they were afraid to hit the spikes with the virtual hand, while 29 participants stated that the

Table 5. *Spearman Correlations between Ownership (O), Agency (A), Change (C), Threat (T), and Collisions (Col) When Embodying the Hand Model (HD)*

	O_HD	A_HD	C_HD	T_HD	Col_HD
Ownership HD	–	.549**	−.084	.461**	−.088
Agency HD		–	−.115	.406**	−.221
Change HD			–	.030	−.086
Threat HD				–	−.250
Collisions HD					–

$^{*}p < .05$ (2-tailed), $^{**}p < .01$ (2-tailed).

Table 6. *Spearman Correlations between Ownership (O), Agency (A), Change (C), Threat (T), and Collisions (Col) When Embodying the Hammer Prosthesis Model (HR)*

	O_HR	A_HR	C_HR	T_HR	Col_HR
Ownership HR	–	.195	.151	.169	−.032
Agency HR		–	.325*	.019	−.311
Change HR			–	.027	−.022
Threat HR				–	−.362*
Collisions HR					–

$^{*}p < .05$ (2-tailed), $^{**}p < .01$ (2-tailed).

hammer prompted them to hit the dangerous objects while reducing their fear to be harmed:

- *With the hand I had a reflex I expressed verbally like it really hurt, as if it was a mistake to hit. I was afraid it would hurt.*
- *I felt like I could hit harder with the hammer! I felt like it couldn't hurt me.*
- *With the hammer I told myself that it was my hand, but that it was more powerful and that I was in less danger. My real hand became the hammer.*

4.3 Correlations

Spearman's rho correlation coefficient was used to assess the relationship between ownership, agency, perceived change, threat, and the number of collisions with dangerous objects for both the hand (see Table 5) and the hammer prosthesis (see Table 6) models.

Regarding the hand, we observed a strong positive correlation between ownership and agency, $rho = .549$, $n = 40$, $p < .001$. There were medium positive correlations between ownership and threat, $rho = .461$, $n = 40$, $p = .003$, as well as agency and threat, $rho = .406$, $n = 40$, $p = .009$. These correlations indicate that the higher the sense of embodiment over the virtual hand, the higher the danger perception.

When it comes to the hammer prosthesis, we observed a medium positive correlation between agency and the perceived change in the body schema, $rho = .325$, $n = 40$, $p = .041$. We also observed a medium negative correlation between threat and collisions, $rho = -.362$, $n = 40$, $p = .022$. These results revealed that a higher sense of agency with the hammer prosthesis led to a higher perceived change in the body schema, which is most interesting considering the lack of visuomotor synchrony (no fingers). Moreover, the lower the perceived danger during the threat trials, the higher the number of collisions with the spikes.

5 Discussion

5.1 Embodiment of a Nonanthropomorphic Limb

As hypothesized (H1.1), our results revealed a significantly higher sense of ownership over the virtual hand model compared to the hammer prosthesis (see Table 4 and Figure 4). This result is in line with previous research (Argelaguet et al., 2016; Lin & Jörg, 2016) where more realistic hand models induced a higher sense of ownership under congruent visuomotor stimulation. Nevertheless, the ownership scores for the hammer prosthesis remain quite high with above-average mean scores on the semantic differential scales. We expected that the addition of the wristband in both the real and virtual environments might have acted as a bridge fostering identification with the virtual limb to compensate for the difference in body ownership scores. The contribution of the wristband will be discussed in more detail in the following section.

Additionally, it is worth mentioning that the qualitative analysis revealed that several participants perceived minor differences between their real hands and their virtual counterparts (e.g., nails, veins, hairiness). While we were unable to observe the impact of such differences in the quantitative results, the impact of hyper-realism requires more investigation considering that modern pipelines allow for the production of very realistic models even for real-time 3D content. This phenomenon might sound closely related to the uncanny valley theory, where realistic virtual humans fail to attain a lifelike appearance, inducing a revulsion response in return (MacDorman et al., 2009; Mori, 1970; Mori et al., 2012). However, what we observed in this experiment was more related to the fact that the 3D hand models closely matched the demographic characteristics of the participants and minor cues led some participants to notice differences that were detrimental to the sense of body ownership. In this context, less realistic or more abstract hand models would likely have prevented such feedback.

Surprisingly, no significant difference was observed in terms of agency between the limb models (see Table 4). Both models recorded average scores over six out of seven on the post-experiment questionnaire with a very low standard deviation. We expected participants to perceive higher motor control with the virtual hand model due to finger tracking (H1.2). It seems that limiting the synchronization to the forearm movements doesn't prevent the induction of a sense of agency over nonanthropomorphic models under temporally synchronous conditions, which is consistent with the priority principle introduced by Jeunet et al. (2018). Additionally, participants perceived a higher change in their body schema when embodying the hammer prosthesis (H3). Interestingly, despite the lack of haptic and/or pseudo-haptic feedback regarding the weight of the prosthesis, its visual properties made out of wood and steel were enough for some participants to perceive that their own limb was heavier. What is most interesting here is that this perception of a change in the body schema was correlated with the sense of agency. The higher the feeling of motor control over the actions performed with the hammer, the higher the perceived change in the body schema. A high change score as recorded by the dedicated dimension of the VEQ (Roth and Latoschik, 2020) is not required to embody virtual characters (e.g., characters closely resembling users), but it might favor the induction of behavioral modifications as described by the Proteus Effect (Yee and Bailenson, 2009) and its underlying self-perception theory (Bem, 1972).

5.2 Perceived Contribution of the Wristband

One of the primary goals of this experiment was to investigate the potential impact of the virtual reproduction of a wristband worn by the participants in the real world. We hypothesized that it could have contributed to improving the sense of embodiment over a non-organic virtual limb (H2). The initial idea was to create a bridge between the real and the virtual environments to foster the identification when controlling the hammer prosthesis. Our subjective quantitative analysis based on psychometric questionnaires failed in demonstrating either a significant interaction effect between the independent variables or a significant main effect between the participants wearing the wristband and the control groups. Post-hoc analyses revealed no effect of participants' gender, nor of their habits of wearing a wristband near their dominant hand in their daily lives. As a limit we will discuss further in the dedicated section, some participants mentioned that they did not pay attention to the wristband during the experiment, despite the embodiment phase and the free movements they had to perform at the beginning of the immersion session in the virtual environment.

Based on the aforementioned quantitative results, we cannot validate our second hypothesis (H2). However, these results must be put into perspective regarding the comments we collected during the semistructured post-experiment interviews. Indeed, as reported in the Results section, several participants explicitly mentioned the fact that the wristband contributed to the identification with both virtual limbs and that it may have contributed to induce a sense of ownership over them. While we have been unable to demonstrate this effect from an empirical standpoint, potential future investigations are suggested in the next section to determine the factors that differentiate participants who may benefit from this effect.

5.3 Anthropomorphism and User Behavior

In accordance with our fourth hypothesis (H4), the reported results revealed behavioral changes induced by the appearance of the embodied virtual limbs. Objective behavioral data, as well as quantitative and qualitative subjective data, all converge towards the same conclusions. First, danger perception was positively correlated with participants' sense of ownership and agency over the virtual hand (see Table 5). As a result, participants avoided more collisions with the dangerous objects during threat trials when embodying the hand. This observation is inconsistent with the results of Argelaguet et al. (2016), where no difference in avoidance was observed when facing potentially dangerous obstacles. Second, embodying the non-organic hammer prosthesis reduced danger perception when facing the spike and higher speeds in users' movements were recorded. Our behavioral measures demonstrated that participants hit more dangerous objects with the hammer prosthesis, even considering the fact that they did not receive any explicit instruction in order to record their spontaneous reactions. In addition, significantly higher average velocities were recorded with this model in both normal and hazardous trials.

While the sense of ownership over the non-organic virtual limb was lower compared to the virtual hand, both virtual limbs received high ownership scores, as well as very high agency scores. Therefore, we argue that the observed modifications in participants' behavior were not induced by a lower sense of embodiment, but rather by an actual impact based on the organic versus the non-organic nature of the embodied limbs. These results are in line with previous research focusing on the potential of virtual embodiment in impacting user behavior (Banakou et al., 2013; Gorisse et al., 2019; Kilteni et al., 2013; Yee & Bailenson, 2009) based on both objective behavioral and subjective data.

6 Limitations and Future Work

Following the proposed protocol, we were unable to observe any significant contribution of the wristband on the participants' sense of embodiment over the virtual limbs from a quantitative perspective. Nevertheless, several participants in the group who experienced the virtual reality application with the wristband stated in the semistructured interviews that it contributed to the identification of the virtual limbs as part of their own body. To identify a potential factor making the wristband relevant to some participants, we performed additional statistical analyses to test a couple of demographic variables, such as gender or the habit of wearing a wristband near the dominant hand, with no success. It should be noted that some participants explained that they didn't pay attention to the wristband during the experiment. The color of the wristband and the weak contrast with some hand models (dark skin tone) and with the wood color of the hammer prosthesis might explain the lack of significant results. Another explanation raised by some participants was that the wristband was not relevant regarding the task they had to perform and that the use of a glove or mitt (only compatible with the hand condition) may have contributed to self-identification.

Using more abstract representations may have helped to address another limitation induced by hyper-realism. Indeed, several participants explained that minor details made them realize that it was not their real hand (e.g., nails, veins, hairiness). Results revealed very high embodiment scores with the virtual hand, but as we approach photorealism it might be possible that more abstract representations may prevent users from comparing their real limbs to their virtual counterparts. Future studies could focus on investigating the relative contribution of realism and truthfulness (similarity between users and their virtual body (Garau, 2003)). Based on feedback gathered throughout this experiment, we assume that highly realistic and demographically congruent virtual limbs make users focus on cues leading them to conclude that it is not their body. Answering such a research question would require a large panel, as the effect size of such a phenomenon is most likely small compared to multisensory integration from an embodiment standpoint.

7 Conclusion

We designed this study to investigate the potential contribution of a wearable item on the sense of embodiment in an immersive virtual environment. Participants were equipped with a real wristband reproduced in the virtual environment. They had to embody both an organic (hand) and a non-organic limb (hammer prosthesis) following a mixed between-within subjects design. We did not observe significant differences between the participants wearing the wristband and the control group. However, post-experiment semistructured interviews revealed a relevant contribution of the wristband in the identification process for some participants, suggesting that there might be some interindividual differences that would make the wristband relevant to some users. Overall, results demonstrated that participants were able to feel a significantly higher sense of ownership over the virtual hand compared to the hammer prosthesis, although the latter still recorded fairly high scores. Furthermore, both limbs induced a very high sense of agency, even considering the lack of visuomotor synchrony of the hammer prosthesis (no fingers). Correlation analyses revealed that the higher the sense of agency over the prosthesis, the higher the perceived change in participants' body schema. Lastly, qualitative as well as both subjective and objective quantitative analyses demonstrated a significant impact of the virtual limb models on participants' behavior. Less apprehension of the virtual threat was reported with the hammer prosthesis. This observation was supported by behavioral data based on the number of collisions with threatening objects and on movement velocity. This experiment further confirms the potential of virtual embodiment to affect user behavior in virtual environments.

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