The Impact of Missing Fingers in Virtual Reality

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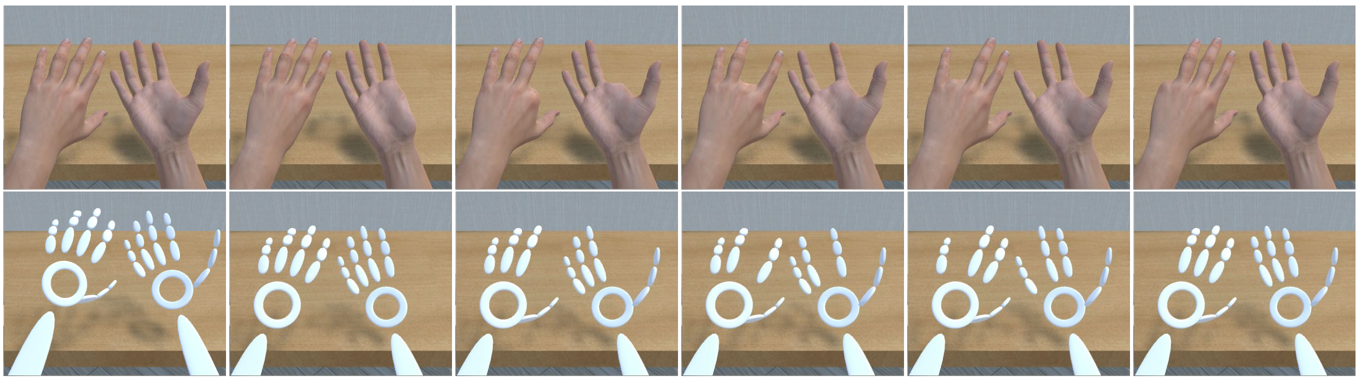

Figure 1: Models of the realistic (top) and abstract (bottom) hand pairs. Fingers are either all visible, without thumb, without index finger, without middle finger, without ring finger, or without little finger (from left to right).

ABSTRACT

Avatars in virtual reality (VR) can have body structures that differ from the physical self. Game designers, for example, often stylize virtual characters by reducing the number of fingers. Previous work found that the sensation of presence in VR depends on avatar realism and the number of limbs. However, it is currently unknown how the removal of individual fingers affects the VR experience, body perception, and how fingers are used instead. In a study with 24 participants, we investigate the effects of missing fingers and avatar realism on presence, phantom pain perception, and finger usage. Our results show that particularly missing index fingers decrease presence, show the highest phantom pain ratings, and significantly change hand interaction behavior. We found that relative usage of thumb and index fingers in contrast to middle, ring, and little finger usage was higher with abstract hands than with realistic ones – even when the fingers were missing. We assume that dominant fingers are firstly integrated into the own body schema when an avatar does not resemble one's own appearance. We discuss cognitive mechanisms in experiencing virtual limb loss.

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CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; *Interaction devices*; • **Computing methodologies** → *Perception.*

KEYWORDS

virtual reality; avatars; missing fingers; phantom pain; presence

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1 INTRODUCTION

Developers and designers of virtual reality (VR) applications seek for creating a sense of presence – the core experience of 'being' or 'acting' in a computer-generated environment even when the own body is physically situated in another place. As presence increases when the user is embodied with a virtual avatar – the virtual representation of the user – VR applications, such as games, often use hand and body tracking technologies allowing precise registration of the own limbs and mapping body movements onto animations of the virtual avatar.

Hands and fingers are commonly rendered in VR applications to provide an intuitive interface for interaction and control of the immersive experience. Character designers of games and immersive applications often stylize their avatars or refer to existing content. Four-fingered alien characters, for example, in *James Cameron's Avatar – The Game* are designed according to the designs of the movie [36]. Altered body structures can also be found, for example, in *The Smurfs Game Series* [23], *The Simpsons Game* [20], the *Crash*

Bandicoot Series [1] or the LEGO computer game series [35]. However, little is known about the effects of avatars with altered body structures on the user in VR. Previous work found that the number of missing fingers negatively correlates with the degree of presence [28]. The higher the realism of the virtual embodiment and the more fingers are missing, the lower the sensation of presence.

In this paper, we investigate how missing fingers affect the VR experience and the usage of the remaining fingers. Fingers were reduced on realistic human as well as on abstract hands in a user study with 24 participants. We found that particularly missing index fingers decrease presence and show the highest phantom pain perception. We also found that the relative usages of thumb, as well as index fingers, were higher while using abstract compared to realistic hands.

2 RELATED WORK

The herein presented investigation is related to research of the phenomenons of presence and limb ownership. We present research on visual-haptic integration and altered body structures.

2.1 Presence and Limb Ownership in VR

Minsky [21] introduced the concept of telepresence for human operators interacting through a remote video robot. Computer-generated illusions through head-mounted displays (HMDs) show that the concept of presence also exists for VR [16, 26, 34]. Sheridan [32] found that presence in VR is a multidimensional construct and defined sensory information, sensor control, and motor control as underlying factors. Lombard and Ditton [16] reported that the mediating technology "appears to be invisible or transparent". Slater et al. [33] and Usoh et al. [37, 38] further stated that presence is the extent to which the virtual environment (VE) becomes the dominant reality or the VE is remembered as a place. Presence is typically assessed using standardized questionnaires [27, 34, 40]. Schwind et al. [29] suggests to measure presence within the VR in order to reduce the variance of presence scores between different conditions. The authors recommend the igroup presence questionnaire (IPQ) questionnaire by Schubert et al. [27] which best reflects the construct of presence for in-VR use as measure among other established presence measures [29].

Presence in VR significantly increases when users are embodied using avatars and experience the illusion that the virtual body belongs to them [5, 17, 37]. The so called illusion of body ownership is based on the assumption that visual and haptic cues from the own body are being combined into a unified percept [9, 29]. Combined cues from the same event such as simultaneous stroking of one's hand while seeing an artificial hand is already known from experiments in the real world to induce the impression that the fake limb is their own [6]. Yuan and Steed [43] found that this paradigm can also be transferred to VR and that the illusion of having virtual hands belonging to the own body rather exists for human-like hands than for abstract effectors [43]. This was supported through further experiments [3, 15, 19], however, not while using high-levels of realism and where a visual mismatch between the real and the virtual bodies can occur, for example, through the wrong gender [30] or the uncanny valley [18, 22, 39].

Figure 2: Participants in the real world (top) and their avatars in VR (bottom) playing the keyboard, turning dice, and completing the virtual questionnaire.

2.2 Altered Body Structures

Researchers have used perceptual conflict to understand cognitive processes of limb integration. The integration of semantic information about the human body and violations of anatomical structures has been investigated using amputees in the real world as well as with avatars in VR. In an experiment with hand amputees and normals, Giummarra et al. [10] induced illusions of embodiment without simultaneous stroking or stimulation of a participant's hand and found that perceiving phantom pain sensations and illusory embodiments do not necessarily require amputation. In VR, the illusion of body ownership was more apparent when the hand was threatened for both amputees, as well as normals, which supports the assumption that body ownership is rather a top-down process while experiencing phantom sensations after limb loss is caused by a bottom-up conflict between the brain and the nervous system [7, 8].

One example of a top-down process causing behavioral changes using altered body structures is known as the Proteus effect [42]. The visual appearance of the own avatar is being associated with stereotypical behavior from previous knowledge and engage users to behave correspondingly [4, 13]. Practical problem arising in human-computer interaction (HCI) concerns the mapping of e.g. animal avatars with the physical body structure of the user and the behavioral implications still allowing high levels of ownership [14].

3 METHOD

Related work found that a cognitive process uses semantic knowledge about the human body structure to incorporate perceived limbs into the own body schema. Due to their importance in immersive VR applications, we investigate if hand avatars with individual missing fingers differently affect presence, phantom pain perception, and if the fingers' usage depends on the missing digits or the realism of the avatar.

3.1 Study Design

We used a within-subject design with the two independent variables Fingers (*all fingers*, *missing thumbs*, *missing index fingers*, *missing ring fingers*, *missing little fingers*) and Realism (*abstract* and *realistic*) resulting in 12 conditions. We collected quantitative data using questionnaires in VR as suggested by previous research indicating that surveying participants during the VR experience reduces the variance of presence scores [29]. To measure the sense of presence, we used the IPQ by Schubert et al. [27] consisting of 14-items. To assess the participants' perceived phantom pain, we used the visual analog scale (VAS) as psychometric response which is a common measurement instrument in clinical studies [11, 12, 25]. We explicitly asked participants to rate their pain perception *related to their hands* using a continuous slider with the two end points "no pain" and "worst possible pain". Additionally, we assessed the frequency of finger collisions with the virtual objects in order to determine finger usage. All fingers (including the missing ones) received virtual colliders, which registered an intersection with the 3D target objects (dice, keyboard, and user interface elements of the questionnaires). Inspired by previous work [28, 30], two tasks were designed to facilitate an immersive VR experience with the virtual hands in the field of view of the user during each condition. As all fingers could be used to solve those tasks, participants were free to choose which hand and which fingers they wanted to use.

In the *keyboard task*, we asked participants to play sounds on a virtual piano. Black and white keys during the task were randomly illuminated and had to be pressed to play a sound. In the *turning dice* task, the participants had to rotate three hand-sized cubes with numbered faces and to lay them correctly on the virtual table in front of them. Numbers on the upper sides of the cubes had to match a random sequence of three numbers on the virtual display behind the table.

3.2 Apparatus

Our application was developed using the Unity3D game engine (v. 2019.3.8f) with a target frame rate of 90 frames per second (fps). We used a Oculus Rift CV1 as HMD and a Leap Motion sensor for hand tracking. The Leap Motion sensor was attached using a 3D printed frame at the front of the HMD. Our software ran on a PC with Windows 10, an Intel i7-8750H, 16GB RAM, and a NVIDIA GeForce GTX 1060 graphics card. The virtual scene was a white room with a wooden table on which the tasks were performed. The participant in the real world sat on a chair during the experience in our laboratory as shown Figure 2.

The virtual hand pairs used in this study are based on previous work and the project files provided by Schwind et al. [28][1]. All hands used the same virtual hand rig and finger tips as colliders for interactions. To avoid gender mismatches [30], we used an androgynous hand model without explicit gender cues for realistic hand pairs for male and female participants. Abstract hands are based on previous work [3, 28, 30].

3.3 Procedure

After welcoming the participants, we explained purpose and course of the study, gave them a brief introduction about the apparatus, and asked them to sign an informed consent form and to complete a demographic questionnaire. We explicitly highlighted that participants could perceive sensations of phantom pain and withdraw or discontinue participation at any time without penalty or losing their compensation. After reading and signing the consent form, every participant was asked to take a seat in the middle of our VR laboratory (see Figure 2). We explained the functionality of the HMD as well as the hand tracking sensor. Condition order was given by a 12×12 balanced Latin square design. Participants started after one minute after familiarization with the first condition. First task was playing the keyboard lasting 1 minute, followed by the turning the dice tasks lasting another minute. After completing all conditions, participants had the opportunity to provide general feedback.

3.4 Participants

We recruited a total of 24 participants (14 female, 10 male) through our university's mailing list. Mean age of the participants was 23.25 ($SD = 4.16$) and ranged from 19 to 39 years. We had 17 right-handed and 7 left-handed participants in our study. All participants had light skin tones matching the visual appearance of the realistic virtual hand pairs. All participants were compensated with credits points for their study course. The study received clearance according to the ethics and privacy regulations of our institution.

4 RESULTS

Shapiro-Wilk test of normality was used to investigate the assumption of normal distribution of all measures. The results indicated non-trivial violations of normality among multiple groups between all indices ($p < .05$). Thus, we applied aligned rank transform (ART) for nonparametric multiple factor analyses using the ARTool package for R by Wobbrock et al. [41] for hypothesis testing. Participant was entered as a random factor in all analyses. All pairwise cross-factor comparisons are Bonferroni corrected.

4.1 Presence

A two-way repeated measures analysis of variance (RM-ANOVA) revealed a significant main effect of Fingers, $F(5, 253) = 5.456$, $p < .001$, however, not of style Realism, $F(1, 253) = .273$, $p = .602$, and no interaction effect of Fingers × Realism, $F(5, 253) = 1.240$, $p = .291$. Pairwise comparisons using Wilcoxon signed-rank tests revealed a significant difference between *all* and *missing index fingers* ($p = .048$). Others were above α-level 0.05. Mean scores are shown in Figure 3.

4.2 Phantom Pain

Using a two-way RM-ANOVA we found significant main effects of Fingers, $F(5, 253) = 5.050$, $p < .001$, and Realism, $F(1, 253) = 15.224$, $p < .001$, and an interaction effect of Fingers × Realism, $F(5, 253) = 5.652$, $p < .001$.

Post hoc comparisons using Wilcoxon signed-rank tests revealed interaction contrasts between *all fingers* and *missing index fingers* ($p = .032$), *missing index fingers* and *missing little fingers* ($p = .013$), *missing index fingers* and *missing ring fingers* ($p = .002$), *missing index fingers* and *missing thumbs* ($p = .002$), *missing middle fingers* and *missing ring fingers* ($p = .026$), and *missing middle fingers* and *missing thumbs* ($p = .025$). Other pairwise comparisons showed no significant interaction contrasts (all with $p > .137$). Mean VAS scores are shown in Figure 3.

4.3 Finger Usage

Individual finger usage during the VR experience was determined through the number of virtual intersections between each finger

[1] https://github.com/valentin-schwind/lessfingers

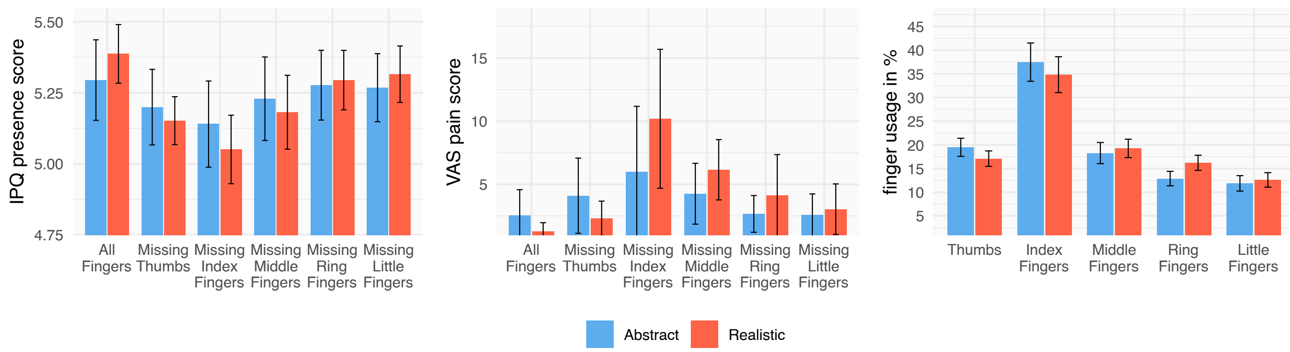

Figure 3: Average IPQ presence scores (l), VAS (phantom) pain ratings (m), and relative finger usage (r) for each condition. Error bars show 95% confidence interval.

tip (including the finger tips of the missing fingers) and the target objects (dice, keyboard, and user interface of the questionnaire).

Thumb usage showed no significant main effects of Fingers, $F(5, 253) = 1.245$, $p = .289$, however of Realism, $F(1, 253) = 22.119$, $p < .001$, and a significant interaction effect of Fingers × Realism, $F(5, 253) = 2.880$, $p = .015$. *Index fingers usage* showed significant main effects of Fingers, $F(5, 253) = 47.942$, $p < .001$, and of Realism, $F(1, 253) = 3.953$, $p = .048$. There was no interaction effect of Fingers × Realism, $F(5, 253) = .295$, $p = .915$. *Middle fingers usage* showed significant main effects of Fingers, $F(5, 253) = 8.422$, $p < .001$, and of Realism, $F(1, 253) = 4.237$, $p = .041$. There was no interaction effect of Fingers × Realism, $F(5, 253) = .295$, $p = .718$. *Ring fingers usage* showed significant main effects of Fingers, $F(5, 253) = 17.328$, $p < .001$, and Realism, $F(1, 253) = 17.747$, $p < .001$, and a significant interaction effect of Fingers × Realism, $F(5, 253) = 3.039$, $p = .011$. *Little fingers usage* revealed significant main effects of Fingers, $F(5, 253) = 8.356$, $p < .001$, however, not of Realism, $F(1, 253) = 4.380$, $p = .037$, and no interaction effect of Fingers × Realism, $F(5, 253) = 1.388$, $p = .229$. Means of finger usage between all tasks and participants (in percent) during the 12 conditions are shown in Figure 3.

Pairwise comparisons of the thumbs' usage showed that their activity significantly differed between *missing index* and *missing ring fingers* ($p = .029$). All pairwise comparisons of finger usage while experiencing *missing index*, *middle*, *ring*, and *little fingers* only revealed significant differences between the *index fingers usage* as well as the other conditions: *all fingers usage* (all with $p < .001$), *thumbs usage* (all with $p < .001$), *middle fingers usage* (all with $p < .001$), *ring fingers usage* (all with $p < .001$), and *little fingers usage* (all with $p < .001$). Differences among the other fingers' usage were not significant.

5 DISCUSSION

Previous work already showed that presence decreases the more fingers of a realistic avatar are being removed [28]. In this work, we showed that this not only depends on realism but also on the individual fingers. Lowest presence scores and highest phantom pain scores were measured using a missing index finger. We observed that presence did not significantly decrease using an abstract avatar and that the reduction of only one finger was not sufficient to show that presence depends on both factors: missing fingers and realism. This is still in line with results of Schwind et al. [28], who found similar results with the removal of little fingers.

Our findings confirm that virtual limb loss causes phantom pain [28]. While these sensations can be explained by a fear of losing the own limbs, phantom pain sensation depends on the individual finger and the realism of the avatar. Highest pain perception was perceived using a missing index finger, however, significantly increases if the avatar was realistic.

As expected, the participants' finger usage showed that they significantly reduced the interaction of the missing index fingers and increased the usage of the other ones when they perceived the illusion of hands without index fingers. However, we found that relative usages of thumb, as well as index fingers, were higher while using abstract hands than with realistic ones. The relative usage of the other fingers increased or decreased contrarily. We assume that human cognition integrates dominant limbs [24] or limbs with the highest functional motor control [2] (thumb and index fingers) firstly into the body schema when the virtual appearance does not resemble the own body. This confirms prior investigations on optimal cue combination showing that haptic stimuli are more likely to be integrated into the body schema when the visual perception ignores non-informative stimuli [6, 9, 31].

Source code, data, and assets to replicate our experiment are available on github[2].

6 CONCLUSION

In this paper, we showed that particularly missing index fingers significantly decrease presence, increase phantom pain perception, and change hand interaction considering the finger usage. We found that the relative usage of thumb and index fingers related to middle, ring, and little finger usage was higher with abstract hands than with realistic hands – independently from the presence of a finger. We conclude that dominant finger limbs are integrated first when the virtual embodiment does not resemble one's own appearance. We assume that an abstract appearance provides less reliable cues about the actual appearance and are less likely to be integrated in an optimal manner.

[2]https://github.com/valentin-schwind/lessfingers-usage

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