"Where's Pinky?": The Effects of a Reduced Number of Fingers in Virtual Reality

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ABSTRACT
The hands of one's avatar are possibly the most visible aspect when interacting in virtual reality (VR). As video games in VR proliferate, it is important to understand how the appearance of avatar hands influence the user experience. Designers of video games often stylize hands and reduce the number of fingers of game characters. Previous work shows that the appearance of avatar hands has significant effects on the user's presence—the feeling of 'being' and 'acting' in VR. However, little is known about the effects of missing fingers of an avatar in VR. In this paper, we present a study ($N = 24$) that investigated the effect of hand representations by parametrically varying the number of fingers of abstract and realistically rendered hands. We show that decreasing the number of fingers of realistic hands leads to significantly lower levels of presence, which is not the case for abstract hands. Qualitative feedback collected through think-aloud and video revealed potential reasons for the different assessment of realistic and abstract hands with fewer fingers in VR. We contribute design implications and recommend considering the human-likeness when a reduction of the number of fingers of avatar hands is desired.

ACM Classification Keywords
H.1.2 User/Machine Systems: Human factors; I.3.7 Three-Dimensional Graphics and Realism: Virtual reality

Author Keywords
Virtual reality; presence; lacking fingers; immersion; avatars.

INTRODUCTION
With the rise of virtual reality (VR) and head-mounted displays (HMDs), the need for understanding how and why the human brain perceives and accepts the virtual world is becoming more and more important. This is particularly relevant for researchers and designers of immersive VR games and applications. A key feature of upcoming VR technologies and games is rendering the user's body in the virtual world using *avatars*. Avatars in VR significantly increase the user's immersion and the feeling of *presence* [11]—one of the key concepts of 'being' or 'acting' in a virtual environment while physically situated in another place. Avatars in VR also provide a natural and intuitive interface for the user to interact with the surrounding virtual world. The most important body parts for interaction through avatars in VR are one's hands and fingers. Using current game controllers, virtual hands can be displayed in VR. Today's technologies even allow motion tracking of hands and fingers without wearing additional motion controllers or markers. Thus, arms, hands, and fingers can be rendered in VR according to their real pose and location.

For video games, however, it is not only important to provide hands for interaction but also to understand how their appearance influences the experience of the user. Designers of video games have unlimited freedom to vary the appearance of an avatar. Cartoonists, for example, simplify their drawings due to the thickness of black outlines. Thus, to avoid too big hands or overlapping of the black outlines, they reduce the number of fingers of their characters. This kind of stylization was adopted and preserved by many video games such as in *Earthworm Jim*, the *Rayman* series, *The Smurfs*, or *Simpsons – The Game*.

Designers can also reduce the number of fingers in realistic ways. In 2009, the cover art of the game *Left4Dead 2* showed a hand with a severed little finger, ring finger, and thumb. To appease the Entertainment Software Rating Board (ESRB) game developer Valve changed the cover in a way that the index and middle fingers remained [19]. In video games, designers reduce the number of fingers in a realistic way as for the aliens in *Avatar – The Game* or Elizabeth's character in *BioShock Infinite*. Thus, the body structure of game avatars in VR does not necessarily match the structure of the user's body. However, little is known about the effects of a reduced number of fingers on the user experience and perception of presence in VR.

To investigate the effect of varying an avatar's number of fingers we conducted a study in VR. We tested five-, four-, three-, and two-fingered hands rendered with a realistic and an abstract style. We collected quantitative and qualitative data. We not only show that reducing the number of fingers significantly affect the perceived presence but also show that this effect depends on the realism of the avatar. This has consequences for VR users and, thus, is relevant for researchers and designers of immersive VR games and applications. We discuss further effects and potential factors that influence the user experience of being in VR with fewer fingers. We contribute implications for game and VR designers.

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RELATED WORK

In the following, we provide an overview of the previous work that is related to the perception of the virtual self and hands in VR. This includes research on the rubber hand illusion, which has contributed to our understanding of own body perception as well as the condition of phantom pain, which is experienced by some amputees in their removed limbs. Both phenomena, established in the real world, pose implications for how one's body avatar ought to be represented in VR. Finally, we discuss how the appearance of virtual avatars affects the illusion of body ownership and the feeling of presence in VR.

The rubber hand illusion experiment by Botvinick and Cohen [4] demonstrated that humans can incorporate prosthetic limbs into their body representation when congruent visual and tactile feedback is provided. Further research of the rubber hand illusion (originally not situated in VR) showed how our body registers the interaction space using self-location [7], self-agency [3], and body ownership [13]. VR allows to further explore the rubber hand illusion from a first person view and for animated false limbs as well as full bodies [23]. The acceptance of structural changes of hands in VR was investigated by Hoyet et al. [10]. The authors examined the rubber hand illusion by using a six-fingered hand in VR. They found that participants experienced relatively high levels of body ownership using an additional finger when compared to using five-fingered hands. Consequently, the authors recommend investigating hands with fewer fingers.

Our work differs conceptually from adding existing body parts in the rubber hand illusion. The removal of limbs is particularly related to work that investigates phantom pain and its treatment in VR. However, it has not yet been investigated how fewer limbs affect acceptance in VR. Murray et al. [16] showed that VR can be used to treat the phantom pain of amputees. Not situated in VR, but also related to our work is the research by Giummarra et al. [9] which compared sensations of amputees and non-amputees. Their findings indicate that both phantom pain and an illusory embodiment, do not necessarily require amputation.

Previous work also shows that the appearance of an avatar affects the VR experience. Lin and Jörg [12] found that more human-like hand models increased the illusion of body ownership. Using a first-person computer-game Christou and Michael [5] found that visual characteristics of the avatar influences the players' behavior. This was confirmed by Argelaguet et al. [1] who found that the appearance of an avatar in VR influences the user's behavior as well. Their results indicate that the sense of agency is stronger for less realistic virtual hands, however, the illusion of body ownership increases for virtual human hands. Peck et al. [17] showed that the manipulation of skin tones caused changes in interpersonal attitudes and decreased participants' implicit racial bias. Not only skin color but also the virtual body size lead to biases in estimating the own weight, which was shown by Piryankova et al. [18].

Research in *presence* is vital, especially as games and virtual environments strive towards becoming more and more immersive. Presence is defined as the "sense of being in another environment" [2] or as "the outcome or a direct function of immersion" [20]. Vinayagamoorthy et al. [25] and Lugrin et al. [14] found that higher degrees of presence were caused by less realistic VR game characters. In both works, the authors assume that their results are influenced by the *Uncanny Valley* phenomenon by Mori [15], who first hypothesized that imperfections of very human-like characters cause uncomfortable sensations. Furthermore, Schwind et al. found gender-related differences when using different virtual hands in VR [21]. Their results indicate that women dislike male hands and men perceive lower levels of presence using non-human avatar hands. The authors suggest avoiding gender swapping in VR by using non-realistic bodies or – if necessary – by using androgyny avatars.

Investigations of the rubber hand illusion [4, 23, 10] and illusion of body ownership [12, 1, 24] are related, but different from the kind of body changes investigated in this paper. They highlight the importance of visual and haptic cues for registering the interaction space of the own body using additional limbs. How the reduction of body parts affects the user experience in VR is currently unknown. For this reason, and especially in context of games, which reduce the number of fingers (*e.g.* for stylized hands), we decided to explore the effects on presence (*cf.* [25, 14, 21]) using avatar hands in VR.

METHOD

Fingers are an integral part of daily interaction and are often removed, for example, for stylization reasons in today's video games. However, previous work did not investigate the effects of removing limbs of VR avatars, however, shows that the degree of realism of the own body has an impact on how users perceive presence. Therefore, we decided to test the effect of fewer fingers with realistic as well as abstract avatar hands in a user study in VR. We used a within-subject study design with the two independent variables REALISM (*abstract* and *realistic*) and FINGERS PER HAND (*two*, three, *four*, *five*) resulting in eight conditions. Data was collected quantitatively through questionnaires in VR and qualitatively through the think-aloud method and video observations.

Stimuli

We compared *five*-fingered hands with hands where we successively removed little finger, ring finger, and the middle finger of each hand (see Figure 1). We used a pinch gesture to trigger events in our apparatus and kept both thumbs as well as index fingers. Previous work found that men and women show different levels of presence while using male and female hands. As suggested [21], we used a human androgynous hand model consisting of a mesh blending between male and female hand models provided by the Leap Motion SDK. To remove an effect of the finger movement on the animated skin at adjacent parts of the palm, we removed the stumps of the fingers. Thus, the hands look more natural and not as being cut off or torn, which was achieved by smooth transitions towards the palm of the hand. A professional 3D artist removed the fingers and the influence of their virtual bones on the hand skin using Autodesk 3ds Max. The abstract hand models are based on the white abstract hands used by Argelaguet et al. [1]. They consist of rigid oval shapes for the fingers and arms as well as a circle-shaped palm.

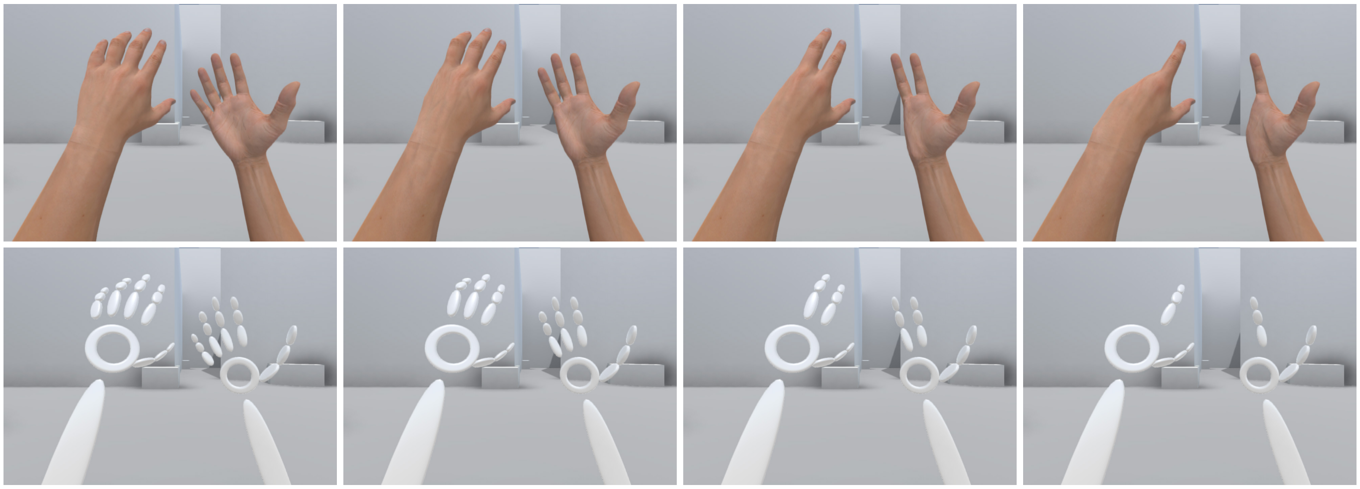

Figure 1. Screenshots of the avatar hand models of the four realistic (1st row) and four abstract (2nd row) hands with five, four, three, and two fingers.

Apparatus

Our system consisted of an HTC Vive HMD and a Leap Motion sensor mounted onto the front of the display using a 3D printed frame. We used a PC with Windows 10, an Intel i7-6700, 16GB RAM, and a Nvidia GTX980 graphics card. Our Unity3D application used hand tracking provided by the Orion SDK of Leap Motion optimized for hand tracking on HMDs. The target frame rate of the application was 60 frames per second. To ensure that the frame rate and the tracking quality was the same for all hands, we used the same tracking system provided by Leap and the same configuration of bones. The surrounding scene was the same for all condition and designed with a neutral white style and a standard sun- and skylight. Real-time global illumination, anti-aliasing, and ambient occlusion were enabled for rendering.

Tasks

Three immersive tasks were used to ensure that the virtual hands are in the field of view of each user. Furthermore, they enabled a versatile and immersive VR experience. We used the tasks purposed and provided by the software by Schwind et al. [21][1]. In the *typing task*, participants operated with a virtual keyboard to enter "I love VR" into a text display. The *draw task* enabled users to perform free hand painting in the surrounding virtual space using the pinch gesture. The *pyramid task* is a physical simulation where participants were advised to staple at least six blocks on a table to build a small pyramid. Black fading was used for transitions between all tasks as well as between the tasks and the final questionnaire.

Measures

We used questionnaires in VR to facilitate a continuously user experience (*cf.* integrated questionnaires in gaming environments by Frommel et al. [8]) as suggested by Schwind et al. [21]. Thus, every participant filled in the questionnaire using the virtual hands whose effect we actually measured. We decided to use the presence questionnaire (PQ) by Witmer and Singer [26]. The questionnaire has been used in a large number of studies, includes items that address related factors such as naturalness or involvement, and all questions can be meaningfully answered in VR. As suggested by previous work [21, 22], we additionally asked for likability, human-likeness, attractiveness, and eeriness on 7-point Likert scales. Participants' feedback and their actions were recorded through think-aloud protocols and video cameras.

Procedure

After signing the consent form, every participant was asked to take a seat in the middle of our VR laboratory. We explained the experimental procedure and introduced the functionality of the HMD as well as the hand tracking sensor. Furthermore, all participants were instructed to "think aloud", which means to verbally articulate all their concerns and thoughts especially considering their virtual embodiments. We pointed out that participants could pause or abort the experiment at any time. The order of the eight virtual hands was given by a balanced Latin square design. The order of tasks was randomized by software. Every task could either be finished by pressing a button or showing a thumbs-up gesture. After completing all tasks a panel with the questionnaire appeared in front of the participant's view. Since all questions could not be displayed at once, panels containing four questions were presented. The participant navigated through these panels of the questionnaire by pressing two buttons labeled "back" and "next". After leaving the VR we handed out a questionnaire where we asked for feedback, general concerns, suggestions. Finally, we also asked for both the hand they prefer and definitely not prefer.

Figure 2. Images of the participants situated and observed in our VR laboratory.

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

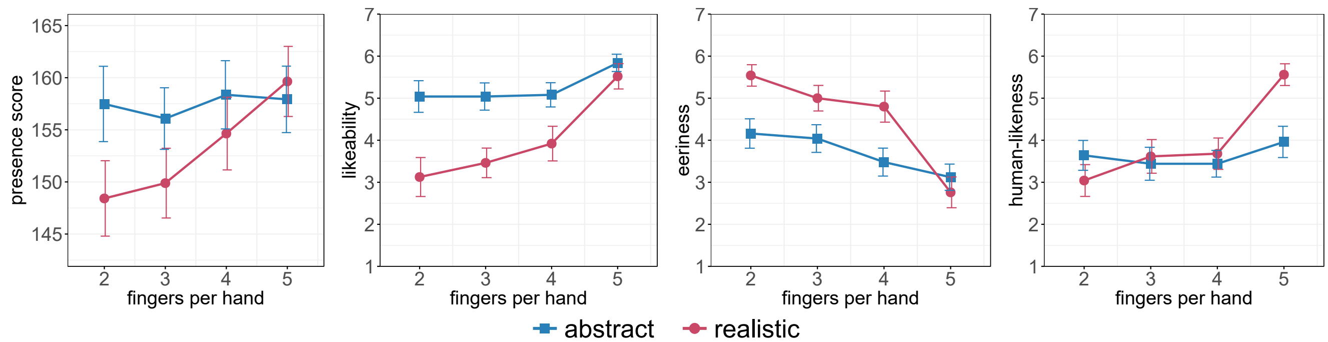

Figure 3. Average presence scores, perceived likeability, eeriness, and human-likeness of abstract and realistic virtual hands with number of fingers per hand. All error bars show standard error of the mean (SE).

Participants

We recruited 24 participants (11 males, 13 females) from our campus via mailing lists and social networks. All participants had light skin tones matching the visual appearance of the realistic virtual hand. None of the volunteers was excluded from participation in the study. The average age of the participants was 21.8 years ($SD = 6.41$). Only four participants mentioned having previous VR experience, 20 of our participants stated that they had no VR experience at all.

RESULTS

On average the study lasted for 75 minutes per participant ($SD = 8.34$). The average task completion time was 3.0 minutes ($SD = 1.8$). Two participants took a 5-minute break.

Quantitative Results

We analyzed the effects of the within-subject factors REALISM and FINGERS PER HAND on our five dependent variables with analyses of variance (ANOVA) using linear mixed-effects models. All effects were taken as random at the participant level. Since we had non-parametric data, we used aligned rank transformations[2] by Wobbrock et al. [27]. All significance levels are at $\alpha = .05$. The results of presence, likeability, eeriness, and human-likeness are depicted in Figure 3. All means (M) and standard deviations (SD) are listed in Table 1.

Presence

A two-way ANOVA showed significant effects of REALISM, $F(1,168.00) = 13.990, p < .001$, and FINGERS PER HAND, $F(3,168.01) = 8.890, p < .001$, on perceived presence. We also found a significant interaction effect between both factors, $F(3,168.01) = 5.890, p < .001$. Pairwise post-hoc comparisons using Tukey's method for p-value adjustment within the levels of the main factors revealed no significant differences of the presence scores between the levels of FINGERS PER HAND using the *abstract hands* (all with $p > .05$). However, the analysis of the *realistic hands* showed significant differences between the levels of FINGERS PER HAND (all with $p < .03$), expect between the *two*- and *three*-fingered ($p = .866$) as well as the *three*- and *four*-fingered hand ($p = 0.066$). Bonferroni-corrected pairwise cross-factor comparisons of REALISM and FINGERS PER HAND revealed significant differences between the *two* and *five*-fingered hand ($p < .001$) and the *three*- and *five*-fingered hand ($p = .021$).

Previous work found an effect of gender using male and female hands [21]. Therefore, we conducted a three-factorial ANOVA including the participant's GENDER as between-subject factor on presence to assess the perception of the used hands. We found no effect of GENDER and no interaction effects of GENDER on REALISM, FINGERS PER HAND, or both (all with $p > .05$). An additional analysis was conducted to determine if participants with previous experiences in VR have potentially influenced the results. We found no effects of PRIOR VR EXPERIENCE as between-subject factor and no interaction effects (all with $p > .05$). The analysis of the quantitative results did not change substantially when persons with previous experience in VR were excluded from the analysis. Therefore, the data of all participants were considered in the analysis.

Likeability

For likeability, we found a significant effect of REALISM, $F(1,168.00) = 33.089, p < .001$, FINGERS PER HAND, $F(3,168.13) = 11.815, p < .001$, and an interaction effect of REALISM × FINGERS PER HAND, $F(3,168.12) = 3.603, p < .015$. Pairwise comparisons showed no significant differences between the abstract hands (all with $p > .05$), but between the *two*- and *five*-fingered, *three*- and *five*-fingered, and *four*- and *five*-fingered realistic hands (all with $p < .001$). Pairwise cross-factor comparisons showed significant differences between the *two*- and *five*-fingered hand ($p = .015$).

Human-Likeness

The measures of human-likeness showed significant effects of REALISM, $F(1,168.00) = 3.956, p = .048$, and on FINGERS PER HAND, $F(3,168.11) = 9.437, p < .001$, and an interaction effect of REALISM × FINGERS PER HAND, $F(3,168.11) = 4.992, p = .002$. Pairwise comparisons showed no significant differences between the abstract hands (all with $p > .05$), but between all realistic hands (with $p < .001$) except for the *two*- and *three*-fingered, *two*- and *four*-fingered, *three*- and *four*-fingered hand. Pairwise cross-factor comparisons showed significance differences between the *two*- and *five*-fingered hand ($p = .001$), the *three*- and *five*-fingered hand ($p = .05$), as well as the *four*- and *five*-fingered hand ($p = .05$).

[2] http://depts.washington.edu/madlab/proj/art/

Realism	Fingers	PQ score		Likeability		Eeriness		Human-like		Attractiveness		Prefer	Not Prefer
		M	SD	M	SD	M	SD	M	SD	M	SD	N	N
Abstract	2	157.480	17.702	5.040	1.843	4.160	1.713	3.640	1.741	4.200	1.876	2	
	3	156.080	14.475	1.843	1.587	4.040	1.612	3.440	1.920	4.520	1.676	2	1
	4	158.360	16.030	4.200	1.412	3.480	1.628	3.440	1.551	4.440	1.675		1
	5	157.920	15.620	1.876	1.007	3.120	1.532	3.960	1.822	5.480	1.473	13	
Realistic	2	148.417	17.364	3.640	2.225	5.542	1.225	3.042	1.815	2.625	1.998		16
	3	149.885	16.714	1.741	1.758	5.000	1.518	3.615	2.000	2.962	1.763		2
	4	154.640	17.085	4.160	2.018	4.800	1.811	3.680	1.827	3.080	1.853		3
	5	159.640	16.473	1.713	1.473	2.760	1.795	5.560	1.267	5.200	1.697	7	1

Table 1. Means (M) and standard deviations (SD) of the quantitative measures (presence score, likeability, eeriness, human-likeness, attractiveness) as well as the number of participants (N) who stated at the end of the experiment to prefer or not prefer an avatar hand.

Eeriness

For eeriness we found significant effects of REALISM, $F(1,168.00) = 11.020, p < .001]$, FINGERS PER HAND, $F(3,168.14) = 17.088, p < .001$, and an interaction effect of REALISM × FINGER PER HAND [$F(3,168.14) = 4.923, p < .001$). Pairwise comparisons showed significant differences between the abstract hands with *two*- and *five*-fingered hands, *three*- and *five*-fingered hands, as well as between *four*- and *five*-fingered hands (all with $p < .05$). We found significant differences between all realistic hands (with p < .001) except for the *two*- and *three*-fingered, *two*- and *four*-fingered, as well as the *three*- and *four*-fingered hand. Pairwise cross-factor comparisons showed significant differences between the *two*- and *five*-fingered hand ($p = .004$) and the *four*- and *five*-fingered hand ($p = .007$).

Attractiveness

We found significant effects of REALISM, $F(1,168.0) = 29.535, p < .001$, and FINGER PER HAND, $F(3,168.1) = 19.2063, p < .001$, on the perceived attractiveness. There was no significant interaction effect between both factors, $F(3,168.1) = 19.206, p = .09$. Pairwise comparisons showed significant differences between the abstract hands with *two*- and *five*-fingered hands, *three*- and *five*-fingered hands, as well as between *four*- and *five*-fingered hands (both with $p < .05$). Differences were significant between all realistic hands (with p < .05) except for the *two*- and *three*-fingered, *two*- and *four*-fingered, *three*- and *four*-fingered hand. Due to the missing interaction effect, pairwise cross-factor comparisons showed no significant differences (all with $p > .05$).

Final Assessments

After having left the VR, a final questionnaire on a sheet of paper were handed out to the participants in which they were asked, which virtual hand they most prefer and not prefer: 13 participants (52%) prefer the abstract hand with five fingers, 7 participants (28%) the realistic hand with five fingers, 2 participants (8%) the abstract hand with two fingers and 2 participants (8%) the abstract hand with three fingers. 16 participants (64%) would definitely not use the realistic hand with two fingers again, 3 participants (12%) the realistic hand with four fingers, 2 participants (8%) the realistic hand with four fingers, and 1 participant (4%) in each case the realistic hand with five fingers, the abstract hand with three, and the abstract hand with four fingers. The numbers of participants which prefer or not prefer the eight avatar hand pairs are summarized in Table 1.

Qualitative Results

We collected qualitative feedback using the think-aloud method and video to gain further insights into the perception of our participants. Based on the records, protocols of verbal utterances and observed actions were transcribed. The transcribed protocols were annotated and scrutinized through axial coding in two iterations: In the first iteration, two researchers went through all comments to identify further individual *factors* and *effects*, which had not been quantified through our questionnaires. One of the authors scrutinized and annotated effects, the other one factors. Both went through the results of the other and refined or complement their results. Discrepancies between the two sets of annotations were resolved through discussion. There was a total of five factors and two effects which were finally identified.

Additional Factors

In the qualitative analysis, we identified *association*, *habituation*, *aesthetics*, *sensitivity to display/tracking errors*, and *task performance* as non-quantified factors which influence the individual experience of the participants in VR. FINGERS PER HAND and REALISM were previously quantified and are not listed as individual factors in the sections below (P# = participant ID; A/R# = abstract/realistic hand and number of fingers per hand).

(1) **Associations:** We found that having fewer fingers were associated with very different prior mental concepts mainly based on the individual experience. Realistic hands with fewer fingers were associated with "claws" (P5, R2), hands of a "T-Rex" (P6, R3) "aliens" (P12, R3), "mutations" (P12, R2), or with the shape of "pistols" (P12, R2). The abstract hands reminded participants on characters from movie or series such as *Wall-E* (P7, A3), *I, Robot* (P7, A2), *The Simpsons* (P23, A4), or on "crabs" (P14, A5), "skeletons" (P1, A2), and "robot" (P13, A5) hand. Associations were influenced by familiarity and previous knowledge: "Abstract hands are much better than realistic hands because it can be that such robots have fewer fingers." (P22, R2). Associations were also connected with the own emotional state and personal feelings: "I feel crippled. I feel sad. When I could see my body, I would be a little crippled sad robot." (P4, A2). Hands with fewer fingers, mainly while using abstract hands, were often considered as practical or functional tools for completing the tasks: "These hands are more practical because I only need two fingers to complete the tasks." (P11, A3).

(2) **Habituation:** For most of the participants the study was the first VR experience. Entering VR and the impression of being in another body was first exciting and overwhelming for them: "Oh my god, this is so cool". (P4, A4). The enthusiasm to be in another body outweighed a potentially strange feeling at the beginning: "Only four fingers? Oh no! But I am so impressed. I could just look at my hands all day. That's so cool." (P12, A4). We further observed that participants accustomed to all virtual hands as well as to a reduced number of fingers: "You get used to dealing with every hand very quickly." (P22, R4).

(3) **Aesthetics:** Participants were influenced by several aesthetic preferences, e.g. design aspects, in particular, while using abstract hands: "Nicely designed." (P16, A4). We assume that design preferences are potentially connected to personal experiences and familiarity: "To see the fingers in such a design is somehow unfamiliar. You should have put a little more effort into it." (P7, A3) We also found that aesthetic aspects depend on the perceived style of the virtual environment: "Everything looks so sterile. You get used to it, however, the robot [abstract] hand fit very well into it." (P4, A5). Aesthetic aspects were also mentioned when using realistic hands: "The place where the finger is missing looks disgusting." (P14, R4)".

(4) **Sensitivity to display/tracking errors:** Hands of all participants were tracked in the same way. However, some participants responded more sensitively to potential errors during hand tracking or rendering using certain hands. Then, even small errors in hand tracking were perceived unpleasant by some participants: "The tracking is really good unless you turn the hand around quickly." (P12, A4). Not only tracking errors, but the overall loss of control of one's own body evoked negative feelings: "I feel to have no control over my middle finger anymore. This is weird." (P12, R3). Some participants had problems with hand tracking that only allowed inputs when visible in the field of view of the HMD.

(5) **Task performance:** We observed that participants became involved into VR when they tried to solve a task, especially the typing task. Completing a task satisfactorily sometimes lead to positive feedback related to the used hands: "I think two fingers are even better to type or paint'." (P4, A2). To complete a task successfully may be influenced by the association (see beforehand) that participants consider hands with fewer fingers as useful tools: "With those, I can type better since I'm not distracted by the other fingers." (P15, A2). Individual performances may be (reversely) related to other behavioral changes which are considered in the following section about individual effects.

Additonal Effects

Furthermore, we identified *emotional reactions* and changes of *hand interaction* as main categories of additional or individual effects, which have not been explicitly quantified through concepts in our questionnaire. We define emotional reactions as initial and prominent short-term responses. Changes of hand interaction are defined as medium-term tendencies for acting and solving problems with hands differently.

(1) **Emotional Reactions:** We observed strong verbal and physical emotional reactions when participants were confronted with *realistic* virtual hands and less than five fingers. They felt "disgusting", "strange", "creepy", "unfamiliar", or "uncomfortable". Partly the participants were incensed. "What the hell is that?" (P6, R3). This was not the case with fewer fingers on the abstract hands: "It doesn't disturb me that I only have three fingers because the hand is not realistic anyway." (P3, A3). However, we recognized satisfaction of participants getting back virtual hands with five fingers after having a hand with a reduced number of fingers. "I have my pinky again!" (P7, A5). Some participants did not initially noticed that there was a missing finger in the *four*-fingered hand condition. They were scared when they finally realized that they are having a *four*-fingered hand.

(2) **Hand interaction:** We observed that participants changed their way of hand interaction when using a reduced number of fingers. Participants only used the fingers they saw. "It is so crazy. I don't move it [the little finger] automatically." (P4, R4). Some participants recognized by themselves changes of their hand interaction which potentially lead to a reverse effect on their feelings and behavior: "It is a totally strange feeling to grab something. You don't expect to be able to hold things." (P12, R4). They also reflect their behavioral changes after getting a *five*-fingered hand: "Now, I move all the fingers instead of just a few, and that is more natural and immersive." (P12, A5). Participants also tried to use haptic feedback of their real fingers to confirm that they are still there: "Yes, I have five fingers. I see four, however, I can still feel my little finger." (P2, R4).

Discussing Potential Cognitive Mechanisms

In a second feedback analysis, two of the authors repeated the analysis of the protocols provided by think-aloud and video. In this iteration, we used axial coding based on the identified factors and effects (see beforehand) to understand why an individual factor has an effect on the user experience. In the following, we establish five potential *cognitive mechanisms*, which may influence an individual's concept of having an avatar with a reduced number of fingers in VR. The themes were discussed and established when they were supported by the feedback from the participants.

(1) **Visually induced phantom pain** caused by the fear of amputation and limb loss lead to strong emotional and behavioral reactions. We observed participants who painted replacements for their fingers at the stumps of their hands during the draw task. "As if you had phantom pain. You feel it, but don't see it." (P5, R4). We also observed that the level of associated phantom pain increased with the number of missing fingers: "So, I can get over one finger. But not two." (P4, A3).

(2) **Familiarity** emerges through individual prior experiences caused by associations. Associations influence personal preferences through knowledge e.g. about threats. Such preferences can then either be positive or negative: "What? Please no! Reminds me somehow of claws of an animal." (P5, R2). Familiarity influences the individual long-term habituation of using hands with fewer fingers, "I have often seen people with

a missing finger, no problem."(P3, R4). And short-term habituation such as with one participant after getting an abstract hand with five fingers: "[...] and now it's freaky to have all fingers again." (P12, A5).

(3) The **Uncanny Valley** by Mori [15] describes a non-linear relationship of familiarity and human-likeness. It predicts a sudden dip of familiarity in relation to the human-likeness (or realism) of a robot or virtual avatar. Since we have only used two different styles (*abstract* and *realism*), our quantitative data does not allow to infer the shape of a potential Uncanny Valley with virtual avatars and reduced number of fingers. However, qualitative data provided while participants used *five*-fingered hands indicate that there is a potential relation to this phenomenon: "Looks strange. I don't know. I liked the other one [hand, A5] more because of the design. Perhaps it's because these hands look more human than the others." (P2, R5), "I don't know, it's confusing because the hand is too real!" (P14, R5).

(4) A **visually induced identity dysphoria** potentially causes discomfort through lacking coherence between the known appearance of one's own body and the virtually projected self. "I feel it's supposed to be my hand. But I know it's not my hand, so I think it is creepy." (P6, R5), The incongruence of the real and virtual body was recognized and lead to a negative sensation, "Hand is too orange." (P22, R5), and using structural changes such as missing fingers in particular: "What is this? I'm not a Simpson!" (P6, R4). "It's completely unfamiliar because you assume that you have five fingers and then you're thinking: Where's pinky?" (P17, R4).

(5) A **mismatch of visual and haptic cues** lead to decreased proprioception and to a feeling of loosing body control. Getting feedback from fingers that were not displayed was considered as a strange and peculiar feeling. "It is totally creepy when I touch my fingers which are not displayed." (P12, R2). The concept is related to the rubber hand illusion [4] when visual cues are in conflict with tactile sensations. This is also related to findings by Costantini and Haggard [6] who interpret that sensory evidence about "me" is related to a prior mental representation of one's own body.

DISCUSSION AND CONCLUSION

In this paper, we investigate how reducing the number of fingers affects the perception of virtual hands in VR. We decreased the number of fingers from little to the middle finger and tested the hands at two different levels of realism (*abstract* and *realistic*).

We collected quantitative data using questionnaires integrated in VR. Our quantitative results indicate that the number of fingers significantly affects presence and shows interaction effects with the level of realism. The reduction of fingers does not significantly influence presence using abstract hands. However, when using realistic hands, the feeling of presence significantly decreased with the number of fingers. The diverging effect of reducing fingers for abstract and realistic hands is confirmed by significant interaction effects for all questionnaire measures except for attractiveness. Furthermore, through reducing the number of fingers, we found significant effects on likeability, eeriness, human-likeness, and attractiveness. Except for the perceived human-likeness, all measures show that the reduction of fingers lead to stronger effects while participants interacted with realistic hands. Ratings of human-likeness were constantly low for all hands, except for the five-fingered human hand, which indicates that the participants had a clear concept of how human avatar hands should look like.

Through the qualitative analysis of think-aloud protocols and videos, we identified factors and effects that were not captured by the quantitative measures. We derived associations, habituation, aesthetic aspects, sensitivity to display/tracking errors, and the individual performance (e.g. while completing the tasks) as additional factors that influence the experience while using avatar hands with fewer fingers. We also found additional effects including emotional reactions and changes of hand interaction. In the second iteration of the qualitative analysis, we discussed five potential underlying cognitive mechanisms: visually induced phantom pains, familiarity based on prior experiences, the Uncanny Valley, a visually induced identity dysphoria, and the mismatch of visual and haptic feedback.

In context of previous research, our paper presents the first investigation of a VR experience with a reduced number of fingers. We examined the effect on presence, thus, our work contributes to a better understanding of the perception of user's self-embodiment and avatars in VR games and applications. Our findings of the mismatch of visual and haptic cues are related to findings of investigations about the rubber hand illusion, however, adding limbs conceptually differs from removing them [4]. The illusion we created is the opposite of experiences with the rubber hand illusion and lead to mainly negative feedback in VR. This is supported by findings of Hoyet et al. [10] who observed relatively high levels of the illusion of body ownership after adding a sixth finger. We assume that self-perception in VR using structural changes that do not match the structure of the user's body depends on whether limbs are added or removed.

Our observations indicate that the reduction of fingers induced phantom pains. The phantom pain of non-amputees could include pain due to the fear of amputation or "real" phantom pains as observed with people with missing limbs, which are also treated in VR [16]. Interestingly our participants responded emotionally, which indicated that they were highly immersed with their appearance in VR and not with the outer world anymore. Nevertheless, the feeling of presence was negatively influenced by reducing realistic fingers. Some shock moments, however, indicate that the participants still had an immersive VR experience. Source code and assets of our project are available on github[3].

Limitations and Future Work

To keep the length of our study reasonable, we only used two different hand styles (realistic and abstract). Cartoon or comic styles, which often make use of four finger hands for stylized characters, should be considered in further studies to examine

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

e.g. also a hypothetical effect of the Uncanny Valley of the own avatar. We symmetrically reduced the number of fingers on both hands. Thus, we could not analyze potential effects of hand or finger asymmetries. Furthermore, we removed little fingers, ring fingers, and middle fingers. Future studies could additionally take thumb and index finger into account. Further research could also investigate the effects of other combinations of removed fingers. For example, it is possible, that the loss of the little finger is easier to handle than the loss of the index finger.

With emotional reactions and effects on the hands interaction, we identified two factors in our qualitative analysis that could be quantified by future research. Furthermore, we derived five potential cognitive mechanisms that influence self-perception in VR with a reduced amount of fingers. To develop a robust and reliable model of virtual self-perception, which also illustrates interrelations and influences the themes, more empirical research is needed. We, therefore, suggest quantifying data of the derived themes to predict potential dependencies and correlations. In line with Schwind et al. [21], we assume that deviations from the own self (e.g. by using altered body scans) should be considered by future research.

VR Game Design Implications

For designers of immersive VR games and applications, we recommend considering the level of realism of an avatar when a reduction of fingers is desired. Using an *abstract* hand style, our VR users felt high levels of presence even with only two fingers left. This was not the case for *realistic* avatar hands. The level of presence decreased according to the number of fingers when using *realistic* avatar hands. Thus, when designers of games create an avatar with less fingers in an abstract way, they profit not only from higher acceptance as opposed to real avatars, but also from less effort they have to spend on implementing highly realistic avatar representations. Emotional reactions of our participants indicate, that a reduction of fingers of realistic hands should only be considered for shocking and horror experiences in VR. We observed habituation effects which potentially indicated that users get used to or even accept hands with a reduced number of *abstract* and *realistic* fingers. However, our participants responded sensitively to any structural changes of the avatar hands. Therefore, we recommend that the number of fingers should be kept consistent during the VR experience or gameplay.

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