Touch with Foreign Hands: The Effect of Virtual Hand Appearance on Visual-Haptic Integration

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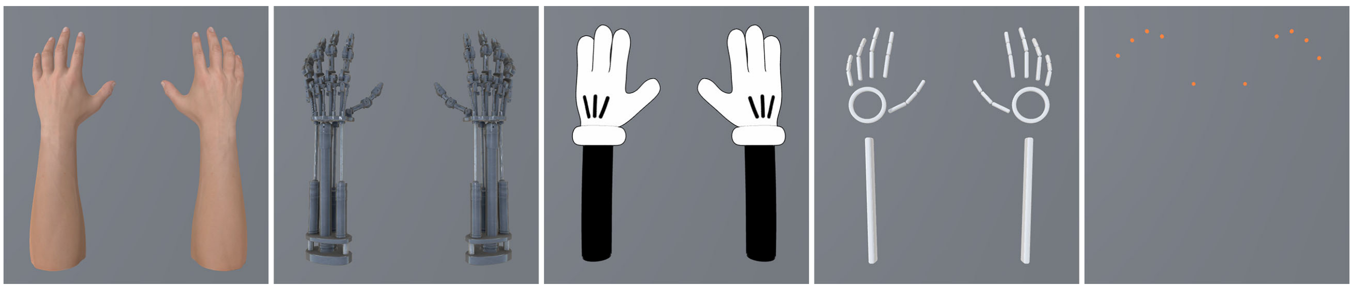

Figure 1: Virtual hand pairs used in our study. From left to right: a realistic *human* hand, a mechanical *robot* hand, a *cartoon* hand, an *abstract* hand, and an *invisible* hand where the position of the finger tips is indicated by flat 2D points.

ABSTRACT

Hand tracking and haptics are gaining more importance as key technologies of virtual reality (VR) systems. For designing such systems, it is fundamental to understand how the appearance of the virtual hands influences user experience and how the human brain integrates vision and haptics. However, it is currently unknown whether multi-sensory integration of visual and haptic feedback can be influenced by the appearance of virtual hands in VR. We performed a user study in VR to gain insight into the effect of hand appearance on how the brain combines visual and haptic signals using a cue-conflict paradigm. In this paper, we show that the detection of surface irregularities (bumps and holes) sensed by eyes and hands is affected by the rendering of avatar hands. However, sensitivity changes do not correlate with the degree of perceived limb ownership. Qualitative feedback provides insights into potentially distracting cues in visual-haptic integration.

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CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **HCI theory, concepts and models**;

KEYWORDS

virtual reality, visual-haptic integration, haptic perception, haptics, avatars, virtual body-ownership, virtual hands

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1 INTRODUCTION

Virtual reality (VR) systems transport people to entirely new environments, provide high-level immersive experiences, and even allow users to take on and control new bodies. Most systems induce immersion through visual and auditory input. Systems with visual feedback about hand position and those with haptic feedback show great promise in inducing even greater immersion (*cf.* [Biocca et al. 2001; Drewing and Ernst 2006; Kalckert and Ehrsson 2014]).

Previous work has shown that displaying properly tracked hands and providing haptic feedback simultaneously increases the illusion of virtual body ownership and the feeling of presence—the feeling of 'being' and 'acting' in VR [Biocca et al. 2001; Sallnäs et al. 2000; Sanchez-Vives and Slater 2005]. However, multi-modal signal generation is challenging because our perceptual systems can be very sensitive to spatio-temporal misalignment across modalities.

Basic research uses conflicts between different sensory cues to understand the limits of this perceptual integration. This research has shown that small conflicts between vision and haptics are often resolved in a statistically optimal fashion, such that each cue is weighted by its relative reliability [Ernst and Banks 2002; Ernst and Bülthoff 2004; Hillis et al. 2002]. In such cases, if the brain deems multiple signals to be originating from a common source, the contribution of each cue to the final percept is proportional to its reliability (defined to be the inverse of the variance of the estimate). The reliability of the combined percept is more precise than the percept from each cue taken in isolation. However, small consistent conflicts can induce adaptation, and large conflicts are noticed and can disrupt the user's sense of immersion [Akiduki et al. 2003; Regan 1995]. It is thus important that multi-sensory stimuli remain calibrated so as not to induce adaptation or break immersion.

In our work, we focus on the question of how virtual hand appearance affects the integration of haptic and visual signals. We focus on this question because it is important for the development of immersive systems to understand how the individual's sense of limb ownership is related to the integration of visual and haptic input. Virtual limb or body ownership is perhaps most widely investigated using the rubber hand illusion. In this famous demonstration, the participant's arm is occluded and stroked in synchrony with a life-sized rubber hand model placed in view [Botvinick and Cohen 1998]. The synchronous visuo-tactile stimulation is such a strong cue that it induces the illusion that the rubber hand belongs to one's own hand. In a similar way, rendering a limb in VR that moves with the users' own one also induces the limb ownership illusion [Kokkinara and Slater 2014; Tsakiris et al. 2010].

Considering VR, the appearance of hands and body can be rendered in any desired artistic style or morphology, and not every appearance induces the same illusion of virtual body ownership. It has been shown, that structural changes, human likeness, or realism of the virtual hand can impact self-perception or the feeling of presence in VR [Argelaguet et al. 2016; Lin and Jörg 2016; Schwind et al. 2017a]. However, it is currently unknown whether and how the appearance of the hand affects the visuo-haptic percept. In a figurative sense as well as in the context of the rubber hand illusion experiment, we are interested in the effect of altering the visual "rubber" on visual-haptic experience in VR.

In this paper, we present the results of a psychophysical experiment examining the impact of the hand appearance on the degree to which visual and haptic signals are integrated. We hypothesize that the more similar virtual hands are to the user's hands, the greater the ownership and that greater ownership makes it more likely that visual and haptic inputs are integrated into a unified percept. With such fused percepts, thresholds for detecting differences will be higher because they will not be able to ignore the uninformative visual cue. This is because the presumably more reliable visual cue will "pull" the combined estimate toward indicating that there is no difference despite the fact that the overall estimate will be more precise. Our results show that the improvement in sensitivity due to multi-sensory integration of vision and haptics is signficanlty affected by the virtual appereance; however, does not correlate to the degree to which the brain incorporates the avatar's hand in the own body scheme.

2 RELATED WORK

In the following section, we provide an overview about previous work in the fields of visuo-tactile perception, limb ownership, and perception of different avatar renderings in VR.

2.1 Visual-Haptic Sensations

Current evidence indicates that visual and haptic sensations for the perception of object properties (e.g., size, shape) are integrated in a manner consistent with statistically optimal cue combination using maximum-likelihood estimation (MLE) [Ernst and Banks 2002]. Combining cues in this way only makes sense if the haptic and visual signals come from the same event. One study demonstrated that while the cues are combined in a statistically optimal way, haptic sensitivity to size difference was not affected by visual feedback indicating that the person was touching and looking at the same object [Hillis et al. 2002]. The implication is that people retain access to the haptic difference signal despite it being combined with the visual signal into a unified percept of size. This result, however, was found in conditions where the visual feedback was very impoverished (e.g., small spheres representing finger tips contacting a one-second stimulus target composed of random sparse dots).

2.2 The Rubber Hand Illusion

The rubber hand illusion experiment [Botvinick and Cohen 1998] is a special case of visual-haptic integration. Simultaneous passive stroking of one's real hand and an artificial limb can lead to a person accepting the fake limb as their own. In comparison to these passive visual-haptic situations, the relationship between the sense of limb ownership and performance in active tasks is less well studied and understood. Della Gatta [2016] demonstrated that active reaching movements are affected by the appearance of the hand. However, these changes in performance do not correlate with the participants' sense of limb ownership. It has also been shown that the illusion of ownership is broken as soon as the person sends a motor command to move the rubber hand and they see that it does not move [Della Gatta et al. 2016].

Kalckert and Ehrsson examined variation in the sense of limb ownership with combinations of visual and haptic feedback in active and passive tasks [Kalckert and Ehrsson 2014] . They found that different combinations of sensory input can lead to a similar phenomenological experience of limb ownership. Our research aims to gain insight into the relationship between the sense of limb ownership and performance in active tasks by visual-haptic discrimination thresholds in conditions where we expect variation in the user's sense of limb ownership. We use hand appearance as a mechanism for varying the sense of limb ownership.

2.3 Virtual Hand Perception

Within virtual environments, Yuan and Steed [2010] found that the virtual hand illusion (the sense of limb ownership for a tracked hand model in virtual reality) rather exists for human-like hands than for an abstract effector. This was supported by Ma and Hommel [2015a], who showed that a realistic appearance boosts the connectedness between real and virtual body. Further research has shown that the degree of human-likeness affects the illusion of body ownership. For example, Lin and Jörg [2016] found that human-like hand models increase the illusion of body ownership. Similar findings were presented by Argelaguet et al. [2016], who found that the appearance of virtual hands also influences the user’s sense of agency. Interestingly, the sense of agency was stronger for less realistic hands, but the illusion of body ownership increased with human-like virtual hands. Similarly, Vinayagamoorthy et al. [2004] and Lugrin et al. [2015] found higher levels of presence in VR using less realistic VR game characters. The authors of both papers assume that presence is affected by the *uncanny valley* phenomenon by Mori [2012]. In two studies, Schwind et al. [2017a; 2017b] found that gender or hand structure given by the number of fingers affect presence using very realistic hands in VR. These findings demonstrate the complexity of the relationships between measures and concepts of presence, body ownership, and agency with virtual hand appearance.

To gain further insights into these relationships, we rely on well-established models of multi-sensory integration and compare measures of performance with direct questionnaire measures of limb ownership. Under the assumption that rich visual feedback increases the likelihood that visual and haptic feedback are fused into a unified non-separable percept (implying that people cannot ignore the visual signal), we expect the sense of limb ownership to be positively correlated with the amount of impact the visual signal has on haptic discrimination thresholds.

3 METHOD

3.1 Study Design

We conducted a psychophysical experiment using the independent within-subject variables HAND (5 levels) and CURVATURE (2 levels). We conducted a two-alternative forced choice (2AFC) task where people were asked to discriminate the height/depth difference in bumps and holes. Our measures are *correct response*, *response time*, and 14 questionnaire items about the touch and hand illusion as well as 8 items about the perceived virtual hand.

3.2 Hand Conditions

We used five different virtual hand conditions that aim to cover a range of variations of human-likeness inducing different levels of limb-ownership. The *human* hand aims to resemble a very realistic hand. Previous work found that specific gender cues of human hands cause distractions and uncomfortable feelings in VR. Therefore, we used the androgynous hands[1] provided by Schwind et al. which were perceived as androgynous and as the most realistic virtual hands in two of their studies [Schwind et al. 2017a,b]. All other hands were modeled using 3ds Max and Mudbox 2017. All hand models use the same skeleton rig with the same degrees of freedom except for the cartoon hands, which had no little finger. The *robot* hands were modeled according to the proportion of the human hand with a mechanical appearance and a glossy metal texture shading. For the four-fingered *cartoon* hands, we used a free Unity3D cel shader[2].

According to previous work that reduced the amount of fingers per hand [Schwind et al. 2017a], we ignored the movements of the little finger by ignoring the influence of the bone on the mesh of the *cartoon* model. The *abstract* hand is a minimalistic representation of a virtual hand. Based on the hand by Argelaguet et al. we used simple primitives (chamfered boxes) indicating the bones’ orientation [Argelaguet et al. 2016]. A torus was placed in the middle of the hand palms. To understand how people perceive touch when no hands are rendered, we used an *invisible* hand. The position of the fingertips in this condition were indicated by small flat 2D-points. All virtual hands are depicted in Figure 1.

3.3 Tasks and Stimuli

To provide haptic feedback, we used convex as well as concave 3d-printed surfaces (*cf.* [Drewing and Ernst 2006; Robles-De-La-Torre and Hayward 2001]). Van der Horst and Kappers [2008] found that curvatures of convex shapes are systematically underestimated compared to the curvatures of concave shapes. We considered these two texture shapes (convex = bumps, concave = holes) as the CURVATURE factor. To compare the influence of these textures, we used spherical bumps and holes, which means that a bump with a height of $0.675mm$ fits exactly into its hole counterpart with $0.675mm$ depth. The range of stimulus height/depth difference required to measure discrimination thresholds was determined in a pilot. The bumps and holes were printed as small plates (measures: $30 \times 30 \times 3.75mm$) with bump heights and depressions ranging from $0.675\ mm$ to $1.05\ mm$ in $0.075\ mm$ steps in their center. All bumps and holes were circular and had a diameter of $15\ mm$.

All 3D printed textures were created using a Stratasys Objet 500 Connex 3 with VeroBlackPlus ABS material and a layer size of $16\mu m$. Bumps and holes received a glossy finish where the omission of printed support material on the model surfaces combined with the UV curing yields a smooth, glossy texture. Standard stimuli for both tasks was defined as the object with the lowest intensity. Previous work found differences in curvature discrimination between one and multiple fingers [van der Horst and Kappers 2007]. We compared bumps and holes only using the index finger of the participant’s right hand. In a 2AFC task, participants had to judge which of two presented textures is higher (bumps) or deeper (holes). Participants were informed that they will touch different physical stimuli but they were not informed that they will see the same virtual stimuli.

3.4 Apparatus

We used a modified robot for stimuli presentation, an Oculus Rift (CV1) for presenting the virtual environment and hands, and an OptiTrack motion capturing system to track markers on gloves and objects on the table. The software application was developed in C# using the Unity3D game engine (v. 5.6.0f3).

We modified a MakeBlock Robot Kit V2.0 for XY plotters[3] to automatically present a stimuli pair in front of the participant (Figure 2). Our Unity application sent commands via serial connection to an Arduino, which actuates the stepper motors that move the rails with the next stimuli to their target position. The robot changed the stimuli pair by moving the two parallel rows, while the virtual object holding the two virtual plates presented at the same position in front of the participant. A button pad with two response buttons was connected to the Arduino to send the participants’ response

[1]https://github.com/valentin-schwind/selfpresence
[2]https://www.assetstore.unity3d.com/en/content/21288
[3]http://store.makeblock.com/xy-plotter-robot-kit/

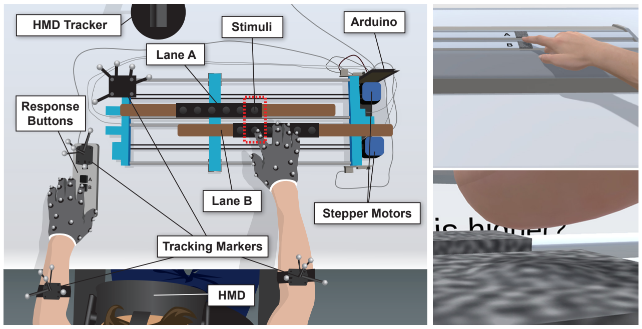

Figure 2: Illustration of the apparatus (l), screenshot of the virtual view (t.r) and close up of the virtual stimuli (b.r.).

back to the Unity application. In VR, both rows and buttons had a fixed labeling (A and B). The robot, rails, and button pad were rendered according to their real position using rigid body markers. The rails with the stimuli were exchanged by the experimenter after each block of trials.

To compensate for potential biases due to the sound of the motors, which were noticeable even while wearing noise-canceling headphones, we shuffled the trials using a heuristic algorithm to ensure that stimuli pairs were never presented twice in succession. At least one of the two stepper motors always moved when a response was given. In a second pilot study (2 m./1 f.), we ensured that participants were not able to notice which of the motors was actuated or in which direction it moved. The shape of the visual stimuli was indicated by a binocular disparity, shadows, and occlusion while the texture cue was an uninformative Perlin noise texture (see Figure 2).

The OptiTrack system for marker tracking consisted of 10 cameras (Prime 17W running at 200 fps) placed in a cage with 150 *cm* width and 100 *cm* height. The system was calibrated using a 250 *mm* wand. The mean 3D projection error reported by the calibration routine of OptiTracks' Motive software was 0.065 *mm*. All robot parts were tracked using rigid body detection and rendered in VR according to their real position. Skeletons and poses of both hands were detected using an unpublished pattern recognition middleware for marker labeling of our institution. No additional IK or collision detection was used. We provided glove pairs in three sizes (L, M, and S), which were custom products made of stretchy and thin polyester mesh permeable to air. Arms were tracked by markers attached using velcro bands at the lower arm. The virtual scene of our application showed a grey table and a simple representation of the tracked objects (see Figure 2). To match the tracking space of hands and rigid bodies with the tracking space of the Oculus Rift head mounted display (HMD), we used rigid body markers on the Oculus tracker.

3.5 Measures

We measured the points of subjective equality (PSE), the just noticeable differences (JNDs) of the standard stimuli compared to the range of bumps and holes, as well as response times. After each condition, we presented an altered version of the Botvinick and Cohen [1998] survey for the virtual hand-illusion adapted by Ma and Hommel [2013; 2015b], Yuan and Steed [2010], as well as Lin and Jörg [2016]. Five additional questions were asked about touch integration, the quality of the system and the perceived appearance in terms of likeability, attractiveness, human-likeness, eeriness, and gender (*cf.* [Schwind et al. 2017a,b]). For each statement, participants chose a rating on a 7-point Likert scale ranging from 1 for 'I strongly disagree' to 7 for 'I strongly agree'.

3.6 Procedure

After an introduction to the protocol of the study and signing the consent form, participants were asked to take a seat and to attach the arm markers, put on the gloves, and put on the HMD. To ensure that participants wore the gloves correctly, they were asked to spread the fingers and make a fist multiple times. During the study they had a place to rest their elbows if they needed to. Once participants were comfortable with the real setup, we showed the virtual scene and introduced the participant in a conditioning phase lasting 1-2 minutes for each hand. The hand conditions were presented in a 5×5 Latin Square design. In each condition, one of the two tasks was presented in random order, and the experimenter exchanged the stimuli (on the lanes of the robot) when necessary. Since there were two rails (Rail B was closer to the participant than Rail A), we presented the standard as well as one of the six comparison stimuli at both positions.

The start of each trial was indicated by the appearance of the virtual stimuli plate and a text in front of the participant with the following questions: "Which bump is higher?" or "Which hole is deeper?" Participants were asked to remove their hands from the apparatus after pressing one of the two response buttons. The end of a trial was visually indicated by the disappearance of the virtual stimuli. After the robot replaced the physical stimuli, the virtual stimuli and question in VR appeared again. Every pair constellation was repeated three times, which resulted in 360 trials per participant. After each hand condition, we gave participants a tablet and stylus to fill in an electronic version of our questionnaire. Subjective feedback of the participants was collected at the end of the experiment. In a short semi-structured interview, we asked participants about their physical and mental well-being, their overall experience, and their hand preference after experiencing the experiment and what they would like to see improved. The complete procedure took approximately one hour.

3.7 Participants

We recruited 41 volunteers (21 m, 20 f), naïve to the purpose of the experiment, through a specialized sourcing vendor, social media, mailing lists, and by word of mouth. Participants were compensated with a $50 Amazon gift card. None of the participants desired a break or quit the experiment. Informed consent was obtained from each participant. The study was approved by our IRB.

4 RESULTS

4.1 Data Analysis

We fit psychometric data with a cumulative Weibull function (2 free parameters, assuming a 0% lapse rate) using quickpsy package for R by Linares and López-Moliner [2016] (see left subpanels in Figure 3). Fitting criteria was the max-likelihood. We took the 75% point on the psychometric function as our measure of one just noticeable

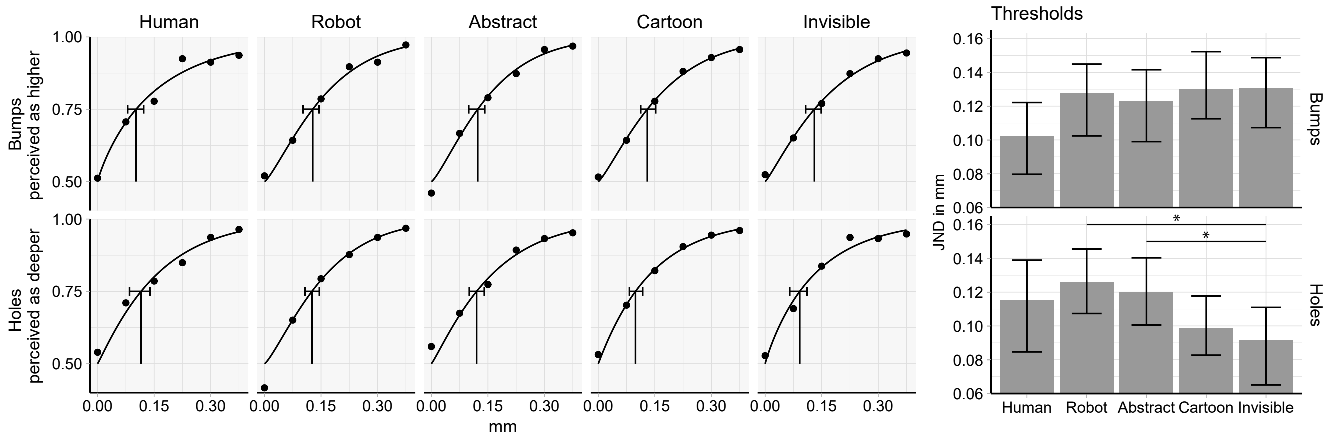

Figure 3: Psychometric data and thresholds of all conditions based on the fitted cumulative distribution functions. The distributions shows the proportion of trials that were either perceived as higher (bumps, 1st row) or deeper (holes, 2nd row). The error bars show the 95% confidence interval.

difference (JND) and used a non-parametric bootstrap procedure with 1000 trials to estimate the 95% confidence intervals on those JND estimates.

At the end of each session, we asked participants to rate the subjective perceived hand ownership index from 1 to 7 in each of the items of the virtual hand illusion questionnaire (Table 1, VHI1-7). These questions have been used repeatedly to assess the different aspects of the virtual limb ownership phenomenon [Lin and Jörg 2016; Ma and Hommel 2013, 2015b]. Additional questions were introduced to assess the fidelity of the rendering and the phenomenology of the tactile stimulation (Table 1, Q1-5). Qualitative feedback was analyzed using axial coding to find related concepts that provide further insights into the visuo-haptic integration of the avatar hands. Two researchers went through all transcribed notes to check each other's coding and to establish consistency in the assignment of codes to the same phenomena. Discrepancies between the two sets of annotations were resolved through discussion. Data of participants who took part in the pilot studies was not considered in the final evaluation.

4.2 Quantitative Measures

Individual JNDs were entered into a two-way repeated measures analysis of variance (RM-ANOVA) with the within-subject factors Hand and Curvature. There were no main effects of Hand, $F(4, 164) = .427, p = .789$, and Curvature, $F(1, 41) = .724, p = .401$. However, there was a significant interaction effect of Hand × Curvature, $F(4, 164) = 3.407, p = .010$. Bonferroni-corrected pairwise post-hoc comparisons of the interactions between the conditions were significant for the *robot* and *invisible*, $\delta = -0.146, t(4) = 9.168, p = .024$, as well as the *abstract* and *invisible* hands, $\delta = -0.146, t(4) = 8.922, p = .025$. For the average response time of the trials on participant level, we included the height differences between bumps and holes as explanatory variable in an RM-ANOVA. We found significant main effects for Curvature, $F(1, 24) = 4.470, p = .034$, however, not between Hands, $F(1, 4) = 1.689, p = .149$, or the Heights, $F(5, 2180) = .902, p = .342$, and no interactions between the factors (all with $p > .05$).

Friedman tests were used to detect significant differences of the subjective ratings indicating virtual limb ownership. The ratings of the virtual hand illusion, their mean values, standard deviations, and the results of the pairwise post-hoc comparisons using Wilcoxon-signed rank tests are shown in Table 1. A multi-variate linear regression analysis of the single measures of the questionnaire items aiming to explain the variance between the JNDs was not significant, $R^2 = .07, R^2_{Adj.} = .013, F(14, 195) = 1.209, p = .270$. We also analyzed the results of the 8 subjective measures to assess the perceived appearance of the hand pairs. The box plots of the appearance assessments and the results of the pairwise post-hoc comparisons using Wilcoxon-signed rank tests are shown in Figure 4. The assessments were also not able to explain the variance between the JNDs, $R^2 = .073, R^2_{Adj.} = .026, F(10, 199) = 1.579, p = .114$.

4.3 Qualitative Feedback

After having completed all judgments and having taken off the virtual headset, all participants indicated that they felt mentally and physically well. One participant stated to be tired, another participant mentioned having stiff hands. No participant complained about motion sickness. We asked participants about their hand preference, their reasoning for giving the answers they gave, what sensations they experienced while touching the objects, and what they would like to improve in the system. Themes were only established when they were supported by the participants' comments. These observations relate to individual participants at the time and allows no general conclusions about the population. However, the subjective feedback provides helpful insights into more underlying concepts and allow to assess the impact of factors which have not been quantified by our objective measures. In our analysis, we found that visual-haptic integration was subjectively affected by the following themes:

Body Structure and Material: Participants mentioned that their haptics were influenced when their body structure differed.

Table 1: Questionnaire results. Items in bold belong to statements designed to test if the hand illusion has occurred. They are either direct ownership questions, or implications or signs of ownership. Friedman tests were used to detect significant differences. Pairwise results are based on Wilcoxon-signed rank tests (H=Human, R=Robot, A=Abstract,C=Cartoon, I=Invisible).

ID	Questionnaire Item	Concept	X^2	H	R	A	C	I	Results
VHI1	**I had the sensation that the touch I felt on my hands was on the same location where the virtual hands were in contact with the object.**	Location-based similarity	9.0	5.7±1.7	5.9±1.1	5.6±1.3	5.7±1.4	4.6±2.1	
VHI2	**I had the sensation that the touch I felt on my hands was caused by the contact of the object with the virtual hands.**	Intersensory Interactions	2.4	6.1±1.2	6.3±1.1	6.4±0.9	6.4±0.9	6.2±1.2	
VHI3	**The movements of the virtual hands were caused by myself.**	Agency	14.3	5.4±1.4	5.5±1.8	5.2±1.8	4.9±1.8	3.9±2.3	**R>C>I**
VHI4	**It seemed my own hands were located in the virtual world.**	Location-based similarity	82.7	4.6±1.7	1.7±1.2	1.8±1.3	1.6±1.3	1.3±1.0	**H,A>R>C,I**
VHI5	**The virtual hands began to resemble my own hands, in terms of shape, skin tone, freckles, or some other usual feature.**	Visual Similarity	4.7	5.6±1.3	5.4±1.3	5.4±1.3	5.3±1.6	4.8±1.7	
VHI6	**It seemed as if what I was feeling was caused by the objects that I was seeing in the virtual world.**	Intersensory Interactions	15.5	4.9±1.5	4.8±1.9	4.8±1.8	4.3±2.0	3.4±2.2	**H,R>C>I**
VHI7	**I felt as if the hands in the virtual world were my own hands.**	Ownership	15.5	4.5±1.7	4.4±2.0	4.4±1.8	3.7±2.0	3.1±2.2	**H,R>C>I**
VHI8	I felt as if my real hands were becoming virtual.	Filler / Control	8.7	5.8±1.5	5.6±0.5	5.9±1.2	5.5±1.6	4.9±1.9	
VHI9	It seemed as if I had more than one pair of hands.	Filler / Control	2.4	2.7±1.8	2.3±1.7	2.3±1.7	2.5±1.9	2.2±1.7	
Q1	I had the sensation that the touch I felt on my hands matched the touch I saw using my virtual hands.	Touch Location	9.1	5.9±1.3	5.6±1.3	5.7±1.4	5.5±1.3	4.7±2.1	
Q2	It seemed as if touching with the virtual hands resembled touching with my own hands.	Touch realism	19.3	5.8±1.4	5.7±1.3	5.5±1.6	5.2±1.7	4.1±2.1	H,R>C>I
Q3	Sometimes I had the feeling I was actually touching the bump/indent that I was virtually viewing.	Filler / Control	7.4	6.0±1.5	5.7±1.5	6.0±1.1	5.7±1.4	5.0±1.9	
Q4	I felt confident in my own measurement judgments of the bumps/indents.	Judgment confidence	4.4	5.8±1.2	5.6±1.0	5.5±1.2	5.5±1.4	5.1±1.7	
Q5	I was able to interact with the environment the way I wanted to.	Agency	7.2	5.7±1.5	5.8±1.3	5.7±1.3	5.7±1.3	4.8±2.0	

The feeling of having hands in VR was better "when they are similar to anatomy" (P7). In particular, participants pointed out that the lacking finger of the cartoon hand lead to perceptual conflicts: "During the cartoon hand I still felt my pinky and it was really distractin". Interestingly, participants mentioned the stiffness of the robot hand: "They made me feel like I was part of a game and it didn't feel uncanny when things were stiff". We observed that the one participant was pressing down on the stimuli very hard using the robot hand. One participant observed that the mechanical parts of the robot hand were not animated: "I'm noticing there's no movement in my arm to move my fingers which is slightly distracting—anatomically. The reflective quality of the metal is nice" (P27). Due to mismatches with their own body participants felt a missing connection to the human hands: "They were not the same skin tone as me. They just weren't my hands" (P26). In the feedback, there were no reports of a preserved difference between physical and virtual stimuli.

Associations: Participants integrated positive, negative, and neutral associations with their virtual appearance. Often they were excited when they felt reminded: "I'm the Terminator!" (P10) or disappointed: "I don't like sci-fi stuff" (P4). The most noticeable result of associations while experiencing visual-haptic integration was distraction: "I love these [robot hands]. So cool! Super distracting though. I'm paying more attention to my hands than the task" (P2). Some associations were brought into connection with task performance: "Reminds me of little pong balls. These don't feel like hands, but are less distracting for completing the task" (P6). Another interesting result of association was empathy: "On an emotional level I can connect with these more and can feel things better [...]. Now I know how Mickey Mouse felt" (P27).

Texture: The participants highlighted differences between the tasks. They felt that either holes were harder to perceive: "I find the holes harder to perceive than the bumps" (P6), or bumps: "The bump task feels more challenging for me" (P26). We also noticed an interaction of hands and task: "They [cartoon hands] are so cute, but hard for the [hole] task because they are so much bigger" (P5).

Summary: Pattern verification of the themes allows some general conclusions about the perceived changes in tactile sensitivity. However, perceived discrimination difficulty in the subjective measures is not necessarily related to the hand preference or to the degree to which the participants integrate the virtual limb in the own body scheme. Furthermore, we learned that participants compared the human hand with their real hand, and even small deviations of the own body were perceived as "creepy" or "disconnecting" while large deviations of the own body were still accepted. This was also observed in other studies and could be partially explained by the previously mentioned uncanny valley [Lugrin et al. 2015; Mori et al. 2012; Schwind et al. 2017a,b; Vinayagamoorthy et al. 2004]. Furthermore, distractions due to associations (positive and negative ones) as well as structural mismatches of the own body can also lead to noticeable conflicts that can influence people's judgments in tactile discrimination tasks as well as virtual limb ownership.

5 DISCUSSION

Quantitative and qualitative data of our psychophysical experiment with 41 participants showed a significant effect of hand appearance on visual-haptic integration and virtual limb ownership. However, the results indicate that the visual-haptic discrimination thresholds of holes and bumps were not systematically affected by virtual limb ownership. This is consistent with previous results indicating that

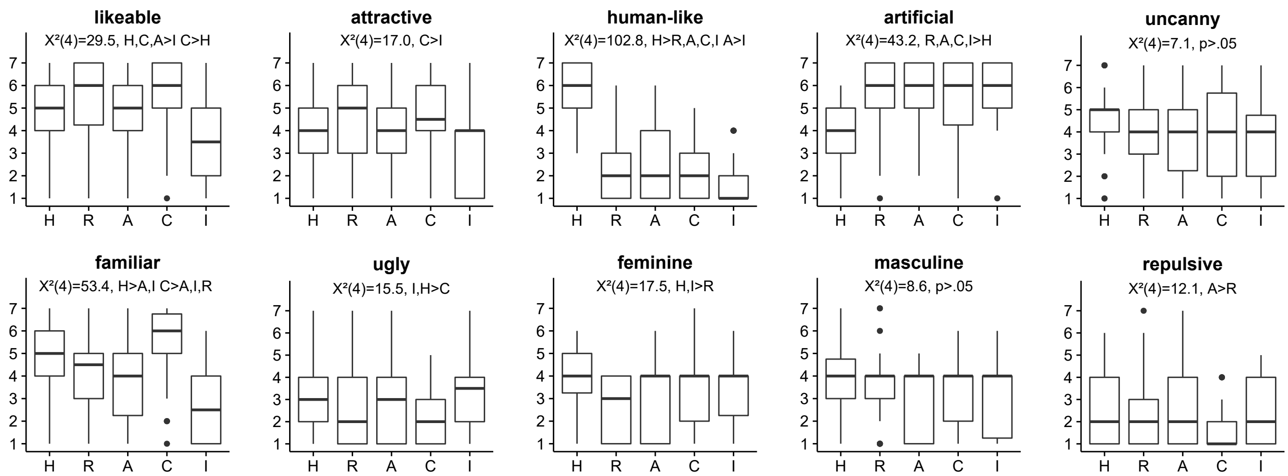

Figure 4: Boxplots and test statistics of the questionnaire results about the perceived hand appearance (ratings range from 1="I strongly disagree" to 7="I strongly agree"). The boxes indicate inter-quartile ranges, the bars show the range of the ratings, and points show outliers. (H=human, R=robot, A=abstract,C=cartoon, I=invisible).

haptic and visual signals can be independently accessed in perceptual judgments [Hillis et al. 2002]. We hypothesized that higher degrees of limb ownership increase the likelihood of visual haptic integration, discrimination thresholds increase with increased limb ownership due to integration of the uninformative visual cue. Results of our measures do not confirm this. Future studies should measure the reliability of the haptic and visual cues independently so that the precise predictions of the mandatory fusion model with MLE can be further tested.

Through qualitative and subjective feedback we found that massive violations of the human-likeness of a virtual hand (*cf.* robot, invisible, or cartoon hand) can affect tactile experiences. As mentioned, they do not necessarily seem to correlate with the degree to which the brain incorporates the avatar's hand into one's own body schema as measured by discrimination performance and virtual limb ownership. Therefore, we assume that more factors are related to the hand appearance (such as the geometrical displacement, perceived mass, shading, or texture) and have independently to be considered in visual-haptic integration.

The interaction effect between hands and curvature indicates that participants seem to be more sensitive to holes than to bumps with less human-like hands, which is potentially caused by the convex shape of the finger tip. This indicates that tactile sensitivity depends on hand appearance as well as on the kind of texture. Due to the round anatomy of the finger tip, more nerve cells in the skin contact the surface of a concave hole than with the surface a convex bump. Thus, the signal while touching holes is more reliable and increases the likelihood of being integrated into the visual-haptic percept. This would explain the increased sensitivity for holes when there are only uninformative visual cues (*e.g.* in the invisible hand condition).

5.1 Design Implications

Do developers or designers of VR applications have to adjust or customize the haptic feedback of devices when different hands are supposed to be rendered and when they aim to provide the same levels of virtual hand ownership? Our results indicate that deviations in virtual hand appearance from the human norm (in our case cartoon, robot, and invisible hands) can affect tactile experience, but do not seem to affect performance in a discrimination task systematically. Subjective feedback from our participants showed that inconsistencies between the visual and haptics experience caused distractions, and thus, led to potentially decreased sensations of virtual limb ownership. However, the diversity of the users makes it difficult to predict when limb ownership occurs. For example, the ratings of the virtual limb ownership were on a relatively high level in their average even for the invisible hand, whose movements were visible only using the fingertip points position.

The analysis of our subjective results indicates that body structure, material, texture, and associations of the users are potentially involved in the visual-haptic integration. For future systems, we strongly recommend to consider the anatomy of the user and to provide synchrony and congruency between the hand rendering and haptics. For example, we do not recommend to render virtual hands with less fingers while haptic feedback is presented for all fingers. Haptic designers can then decide to compensate the intensity of haptic feedback using virtual hands of e.g. "Hulk" or "Terminator" since they are not supposed to have sensitive but heavy and massive hands.

5.2 Limitations

The herein presented study shows that the appearance affects visual-haptic experience, but does not systematically affect objective measures of tactile sensitivity. However, as noted earlier, future studies should investigate the reliability of the haptic and visual cues independently so that the precise predictions of the mandatory fusion model with MLE can be further tested. Importantly, while the visual surface cues to the bump size were fixed, the feedback from tracked motion was consistent with the bump/hole size of the haptic stimulus. It is possible that observers used this motion cue in their depth/height judgments when ignoring the visual surface cues. Another limitation of the study is the usage of gloves. While the bumps and hole sizes were selected to match sensitivity with gloves, it is possible that gloves have affected our results. Future studies could be performed using adhesive markers directly attached to the skin.

5.3 Future Work

More research is required to understand visual-haptic integration while experiencing virtual limb ownership. We found significant differences in the virtual hand illusion questionnaire, but the subjective ratings of the virtual hand illusions were at a relatively high level even when dots were presented in the invisible hand condition. This could indicate that more significant deviations from the human norm are necessary to induce a decreased sense of limb ownership or that motion and that tactile cues are the driving factor for limb ownership. Cue-combination studies could be run to test the relative impact of motion cues and texture cues to limb ownership. It is also conceivable that the results depend on the type of tactile sensations. Touching objects from their sides, for example, differs from touching objects from above. Future research could examine conditions where the reliability of visual and haptic cues varies naturally (e.g., when feeling and seeing your hand touch the two sides of an object as opposed to the front and back). In addition, visual factors must be further operationalized to understand which visual aspect of the hand appearance influences the visual-haptic percept.

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