Understanding Visual-Haptic Integration of Avatar Hands Using a Fitts' Law Task in Virtual Reality

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ABSTRACT

Virtual reality (VR) is becoming more and more ubiquitous to interact with digital content and often requires renderings of avatars as they enable improved spatial localization and high levels of presence. Previous work shows that visual-haptic integration of virtual avatars depends on body ownership and spatial localization in VR. However, there are different conclusions about how and which stimuli of the own appearance are integrated into the own body scheme. In this work, we investigate if systematic changes of model and texture of a users' avatar affect the input performance measured in a two-dimensional Fitts' law target selection task. Interestingly, we found that the throughput remained constant between our conditions and that neither model nor texture of the avatar significantly affected the average duration to complete the task even when participants felt different levels of presence and body ownership. In line with previous work, we found that the illusion of virtual limb-ownership does not necessarily correlate to the degree to which vision and haptics are integrated into the own body scheme. Our work supports findings indicating that body ownership and spatial localization are potentially independent mechanisms in visual-haptic integration.

CCS CONCEPTS

• **Human-centered computing → HCI design and evaluation methods**; **Virtual reality**; *User studies.*

KEYWORDS

Virtual reality; Fitts' law; avatars; visual-haptic integration; depth cues.

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1 INTRODUCTION

Over the last years, virtual reality (VR) received increased attention from various fields such as medicine, engineering, education, design, and entertainment. Head-mounted displays (HMDs) for consumers enable more and more people become interested in VR and increase the demand for applications and content [46]. One of the core challenges of VR is transporting people to another place and inducing presence – the illusion of acting and being 'there' even when one is physically situated in another place. VR systems and applications designed to maximize the feeling of presence for users often make use of virtual characters also known as *avatars.*

Avatars in VR arouse the sense of body ownership [33, 41, 43] and agency [19, 47] as they allow users to locate their own body pose within the virtual environment. For video games and other VR applications, however, it is not only important to provide avatars for spatial localization but also to understand how the avatar appearance is integrated into the own body scheme and influences the experience of the user. It is known that the virtual appearance not only affect the subjective experience of presence [23, 24, 36, 38], but also objective measures suchs as physical movements [7, 18], typing speed [20] or pointing accuracy [30, 40]. Thus, for creating consistent VR experiences it is crucial to understand how human sensations can be optimally integrated into the own body scheme or which factors even prevent integration. For example, previous work already showed that human-likeness [23, 24], gender [38], body structure [36], or transparency [4, 20, 28] of the virtual representation must be considered as they can affect the ownership illusion as well as the users' performance.

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Little is known about a *systematic* relationship between body ownership and visual-haptic integration. As already indicated, mainly synchronous vision and haptics contributes to the illusion that fake limbs belong to the own body – not only in the real world [3] but also in the virtual one [51]. Research has shown that visual and haptic cues are integrated in a statistically optimal manner, which means that each cue is weighted and integrated by its overall reliability [8–10]. Since the reliability of a combined percept is higher than of a single one, it is conceivable that the probability that the virtual limb is being integrated into the own body scheme is also higher when synchronous vision and haptics are presented. Thus, inconsistencies between vision and haptics can cause cue conflicts and decrease the probability that cognition integrates those cues into a unified percept. This could explain, for example, that the extent to which users accept virtual limbs as their own ones seems to correlate with the degree of perceived human-likeness [23, 24, 51] or similarity with the own body [16, 36, 39]. Consequently, previous work hypothesized that the higher the similarity with the own body and, thus, limb ownership, the more likely is that visual and haptic cues are integrated into a unified percept, which, however, could not be confirmed yet [39].

In contrast, prior work rather indicates that the brain integrates vision and haptics according to the paradigms of optimal cue combination to locate the own body, but not while experiencing ownership with an artificial hand [29]. Thus, separate mechanisms of visual-haptic integration underlie ownership and localization of the own avatar, which means that the brain makes a functional distinction between the *who* and the *where* of the virtual body [29]. However, both the illusion of body ownership as well as spatial localization require synchronicity between vision and haptics [3] and a plausible, human-like body structure [1, 36, 44, 45]. Due to the dominance of vision, it is conceivable that visual cues exist that can affect integration and potentially reveal a systematic relationship.

Visual cues include depth cues such as disparity, slant textures, and occlusions, among others. Depth cues can also perceived via haptics such as tactile feedback or proprioception. It is conceivable that users will ignore uninformative and integrate informative depth cues via vision while registering the own body pose via haptics. Incongruities between vision and haptics would negatively affect spatial localization and thus input performance while optimal congruency could even increase both correspondingly. When visual cues are manipulated, an effect of the subjectively perceived body ownership is to be assumed as well. Revealing an effect on body ownership but not on input performance would further strengthen the argument that body ownership and spatial localization are independent mechanisms in visual-haptic integration. To investigate this assumption, depth cues of the own body must be manipulated providing more (or less) information about the own body pose. Effects by increased or decreased spatial localization can then be measured by observing movements controlled by the proprioceptive system.

A model of human movement was proposed by Fitts [11]. The model predicts that the time required to move limbs to a target area is a function of the ratio between the distance to the target and the size of the target. Under certain conditions and means for input, the quantity of information transmitted varies. Previous work used Fitts' law task not only in typical tasks in human-computer interaction (HCI) but also for modeling motion and behavior in VR while experiencing latency, for example [17]. Thus, to further understand the relation between virtual limb-ownership and visual-haptic integration of depth cues on the own avatar, we investigated the effects of the virtual hand appearance on the human motor system using different avatar designs while performing a Fitts' law task in VR.

In this study, we investigate if depth cues changes on geometry and texture of a users' avatar affect the input performance measured in a two-dimensional Fitts' law target selection task. Our results show that mean time and throughput remained constant even when different degrees of body ownership were perceived. This supports previous findings that body awareness and spatial localization of the own body are independent mechanisms. We even argue why the illusion of body ownership is a top-down and higher cognitive process than spatial localization as a bottom-up process even when both processes require synchronicity between vision and haptics.

2 RELATED WORK

In the following section, we provide an overview about previous work on VR avatars affecting the illusion of virtual body ownership, input performance, and human behavior. Based on the task in our study, this work is related to Fitts' model of human movement (Fitts' law).

The Illusion of Body Ownership

The rubber hand illusion experiment by Botvinick and Cohen [3] shows that simultaneous stroking of one's real hand and an artificial one (the rubber hand) makes people to accept the fake limb as their own one. Della Gatta et al. [7] showed that active reaching movements can be affected by the appearance of the hand but do not necessarily correlate with the participants' sense of limb ownership. Nevertheless, the illusion of ownership ends when a person sends a motor command without seeing a moving hand. Kalckert and Ehrsson [18] found that different combinations of sensory input can lead to a similar phenomenological experience of limb ownership during active and passive tasks.

Yuan and Steed [51] found that the rubber hand illusion paradigm can also be transferred to VR. They found that a *virtual* hand illusion rather exists for a human-like hand than for an abstract effector. Similarly, Ma and Hommel [25] found that a realistic appearance increases the acceptance of the virtual hand. This was supported by further studies [1, 23], excepting for studies with very high levels of realism, where a perceptual mismatch with the own body can occur. Such studies indicate that visual realism and self-similarity are distinct concepts. An experiment by Schwind et al. [38] showed that virtual bodies with a different gender are rated as similar in terms of human-likeness, but highly dissimilar in resembling their own self. Further experiments also showed that too realistic bodies with inconsistent realism evoke an uncanny valley effect [24, 32, 48].

Not only the subjective experience of body ownership, but also real movements [1, 7] and objective performance indices can be influenced by the appearance of the virtual avatar. Known performance indices affected by the avatar appearance are typing performance [20] or pointing [30, 40], for example. Using a cue-conflict paradigm Schwind et al. [39] investigated to which extent virtual hands in different styles affect visual-haptic integration. They found a significant effect on tactile sensitivity (e.g., lower thresholds of tactile sensitivity using invisible hands and higher thresholds using robot hands), however, there was no systematic relationship between participants' ratings of virtual body ownership and thresholds of tactile sensitivity. The authors assumed that their results indicate that haptic and visual cues can be still integrated independently even when virtual limb-ownership is perceived to a high degree [39]. This was supported by findings by Matsumiya [29], who found that integration of body ownership and spatial localization via haptics are potentially independent processes.

Fitts' Law (in VR)

In 1954, Paul Fitts proposed that the time, which a person requires to select a target, is a function dependent on the distance and the width of the target. He found that the information capacity of the human motor system can be determined by controlling the amplitude of the movement. As humans' movements are commonly applied to two-dimensional targets MacKenzie and Buxton [26] developed a two-dimensional Fitts' Task defined by the norm ISO 9241-9, which has been revised by ISO 9241-4002007. In that multi-directional task, the targets are arranged in a circle and each target is highlighted to be selected in a fixed order. Variations of different difficulties are classified with the index of difficulty (ID) as shown in Equation 1. Fitts' law is mainly used in the field of HCI to investigate the input performance using different input devices with the unanimous consensus that the mouse is the dominant input device [15, 26, 31].

Fitts' law has been used to test different input modalities in VR. For example, McGee et al. [31] compared the input performance using a typical workstation with a virtual one in order to determine the effects of VR hardware. Interestingly, using an HMD showed no effect compared to the real world setup. Fitts' law was also used to compare a Mattel PowerGlove (a Nintendo GameController) with a computer mouse, whereat the mouse was significantly faster and had significantly lower error rates [15], which underlines the dominance of the mouse as input device in virtual environments. The study most similar to ours was conducted in AR by Mason et al.[28]. In their study, visual as well as haptic feedback were either present or absent. The study shows that movement times are slower when the own body is invisible and remained constant (regardless of target size) when haptic feedback was removed.

Depth Cues

The human brain must infer the three-dimensional world from two retinal images. Disparity, texture, or motion-parallax are cue to reconstruct depth. Using an optimal cue combination paradigm, Hillis et al. [13] found that observers weight and combine each cue to a unified depth percept according to its relative reliability. Rosas et al. [35] investigated how different types of textures (circles, leopard, perlin noise, and 1/f perlin noise) change depth perception and found that textures with a pseudo-random distribution of circles provide the highest reliability in discriminating the distance of objects in motion. Moreover, using a similar set of stimuli Rosas et al. [35] additionally investigated haptic depth cues and found that visual as well haptic depth information fell short of statistically optimal combination. The authors assume an underlying process constructing a depth precept in a manner consistent with a weak-fusion model, which predicts that vision and haptics are linearly and independent combined to obtain depth [6, 21].

The human appearance does not necessarily provide optimal depth cues as designs exist that only provide information about the own body pose. For example, Schwind et al. [40] showed that robot or abstract designs can increase the mid-air pointing accuracy of users in VR while avatars with less depth cues (e.g., cartoon shader) showed reduced accuracy. The authors firstly hypothesized that virtual limb ownership affect accuracy in performing the pointing gesture, however, conclude that visual information through geometry and shading of the own body can improve the sense of spatial localization in VR. Increased accuracy in touch interaction is also hypothesized to be related with hand size [34] and finger dimensions [5] as thinner fingers cause less occlusions using smaller targets [2].

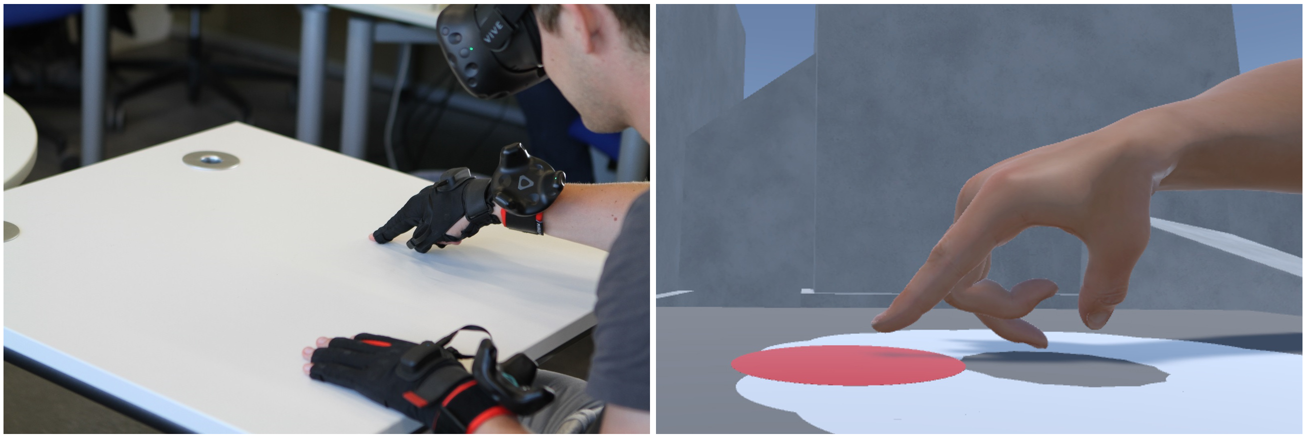

Figure 1: Participant performing the Fitts' task in the real (left) and virtual world (right).

Summary

Previous work could not establish a systematic relation between body ownership and visual-haptic integration [7, 18, 29, 39]. Researchers suggest to examine other factors of the virtual appearance that systematically affect spatial localization as well as body ownership [39]. The manipulation of depth cues on the surface of the avatar seem to be a promising candidate [6, 21, 35], since here (in)consistencies between vision and haptics can affect both spatial localization as well as the illusion of body ownership [20, 28]. A systematic effect could help to understand how one's own appearance is integrated into the body scheme while no effect would support findings that both mechanisms are independent process [29]. Measuring input performance using Fitts' law of human movement [11, 26, 27] is a well-established model to determine effects on the proprioceptive system and on performances in VR [15, 28, 31]. It is currently unknown if depth cues on the virtual avatar can affect spatial localization and, thus, the input performance in VR. As previous work also found effects of hand size [34] and finger dimensions [5] on touch interaction, we also hypothesize a potential relation to systematic changes in model size of the own hand. Therefore, we conducted an experiment to investigate how model and textures of avatars in VR affect the input performance in a Fitts' law task in VR.

3 METHOD

We conducted a study to investigate how different designs of a hand avatar in VR affect the input performance of users in VR. We hypothesize that more depth cues on the virtual avatar improve spatial localization and, thus, input performance. Vive versa, lacking depth cues such as a flat toon shading would decrease input performance. We collected data regarding the users' inputs, demographics, and subjective experiences using questionnaires in VR.

Study Design

We used a repeated-measures (RM) design, with TEXTURE and DISPLACEMENT as two independent variables (IV). Each IV had three levels resulting in 9 conditions. With each hand, the participants had to perform 20 repetitions of a 2D Fitts Task. We used 10 levels of initial indexes of difficulties (IDs) ranging from 2 to 6. The order of the hands was given by a balanced 9×9 Latin square design. The participants had to answer a questionnaire before and after each trial.

Stimuli

We changed the hand representation by varying three levels of TEXTURE and three of GEOMETRY resulting in nine conditions (see Figure2). We used a *human* texture resembling a human hand without explicit gender cues to avoid negative reactions (c.f. [38]), a *pointed* texture with white background and black spots in order to improve spatial localization, and a *flat* shading without any depth cues given by the surface. Shadow casting of the avatar in the flat shading condition was disabled to reduce any depth cues of the virtual appearance.

We used three geometry displacements for systematic changes of the touch experience: normal (*0cm*), thick (*+1cm*), and thin (*-1cm*). The area, which users could touch had exactly same size in all nine conditions. All hands had the same length. We measured the distance between index finger and wrist crease of each participant and used that value to scale the hands in our Unity3D application, according to the real hand. We used that length as opposed to the normally used length between middle finger and wrist crease because the users will use their index finger to interact with the virtual world, so it is most important that the distance to the front index finger feels as close to the real world as possible.

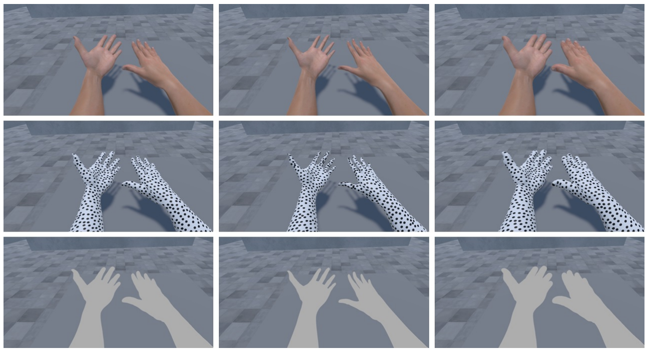

Figure 2: The nine virtual hands. Displacement from left to right: normal, thin, thick. texture

Apparatus

For the study, precise hand tracking was required. Therefore, we used the Manus VR Glove DK1, which is only compatible with the HTC Vive. The Manus VR Glove contains a gyroscope, accelerometer, and magnetometer to track the fingers movements. It uses flex-sensors to measure finger bending and requires gestures (min-max poses) for calibration. Within our Unity scene, we built a table, which resembles the real table in our lab. The table's measurements were 80 cm (w) × 80 cm (l) × 73 cm (h). We mapped the size and position of the table in the real world to the virtual space using an HTC Vive tracker. The collider of the index finger had the same size for every hand and resembles the size of the index finger of the normal sized hand. Users could only interact with the buttons using their right index finger.

Procedure

After getting an introduction about the purpose of the study and signing the informed consent form, the participant took a fixed seat in front of the table. We then measured their hand-size and asked them to put on the Manus VR Gloves. We changed the hand-size in our Unity3D application so that the virtual hands and the participants' hands were equally sized. Afterwards, we had to calibrate the Manus VR Glove for each participant. The calibration required participants to perform four gestures with each hand. Them, we helped them by attaching the HTC Vive trackers to their arms and a participant got the HTC Vive HMD. After putting on the HMD the participants saw a simple table with some instructions for the Fitts' Task. The participants were asked to adjust the lenses of the HTC Vive and make themselves comfortable in the virtual space. Familiarization lasted around 1 min. We told participants to perform the task "as fast and precise as possible". Each hand were presented for around one minute before the task to make participants familiar with them. The sequence of conditions for each trial were ordered using a Latin square.

Measures

We collected data about input performance, presence, and body ownership. Input performance data consisted of the duration between two target selections and the position data of the target selection. We started measuring input data as soon as a participant selected the first red button of one round and the last duration was measured as soon as the last button of the round was selected. We collected data about the participants' presence and embodiment for each virtual avatar hand, using two questionnaires with three questions each. The questionns can be found in Table 1. Questions were asked *during* the VR experience to reduce the variance between the scores as suggested by Schwind et al. [37] using a virtual questionnaire. Participants completed the questionnaire after each condition using the virtual hands whose influence we measured. Items were used based on previous questionnaires asking for limb ownership [1, 23, 39]. The first questions (Q1-Q3) about presence and body ownership were asked after familiarization but before the participants performed the task to avoid biases due to hypothesized changed in input performance. Questions about interaction and touch sensation (Q4-Q6) were presented after finishing the target selection task. Currently, there are no standardized questionnaires of body ownership. Q1 was asked due to its highest inter-item correlation measuring the construct of presence [37], Q2 and Q3 were used for hypothesis testing as suggested by Lin and Jörg [23], Q4-Q6 are based on findings on visual-haptic integration by Schwind et al. [39].

Participants

We recruited 37 participants (30 males, 7 females) via mailing lists of our institution and social networks. All of them were right-handed. Their age ranged from 18 to 29 ($M = 22.49$, $SD = 2.60$). They either received either one credit point for our lecture ($N = 26$) or were reimbursed with 10 EUR ($N = 11$). No volunteers were excluded from the study. One participant's data had to be removed due to him not making an effort to complete the task as best as he could. The data was deleted before the next participant, thus, the Latin square design was not violated. One participant had a lot of VR experience, the rest of the participants stated they had only little to none VR experience. Only one participant stated he is prone to motion sickness but did not feel uncomfortable during his time in VR. No participant desired to quit or pause the study. The average hand length was measured from the wrist crease to the middle fingertip and ranged from 18.0 cm to 23.0 cm ($M = 20.22\,cm$, $SD = 1.81\,cm$). We also measured the length from wrist crease to the tip of the index finger. These lengths ranged from 17.0 cm to 21.0 cm ($M = 19.12\,cm$, $SD = 1.12\,cm$). Avatar hands were scaled based on the real world measures.

Data Analysis

We filtered all samples above a threshold of 4 seconds and, then, outliers which were more than three standard deviations away from the mean. Both filters were applied within every trial. In total, 2.5% of our samples were filtered. Latin square design was not violated as no trial was fully deleted. The effective throughput (TPe) was calculated using the model proposed by MacKenzie and Buxton [26]. The model (see ISO 9241-411 [14]) provides an improved link to information theory, better fits, and IDs that cannot be negative. We calculated the effective index of difficulty (IDe) based on Equation 1:

$$ID_e = log_2\left(\frac{A}{W_e} + 1\right) \quad (1)$$

With A as amplitude (distance between two targets) and W_e as the effective target width calculated by the distribution of targets over a sequence of trials. To calculate the effective throughput (TPe) we used Equation 2:

$$TP = \frac{ID_e}{MT} \quad (2)$$

4 RESULTS

The time participants spent in VR was 49.55 minutes on average (SD = 7.04). Hence, each of our participants experienced one of our conditions ca. 5.5 minutes. Every participant had to select 300 targets per hand (15 targets × 10 IDs × 2 repetitions). Each participant performed 2700 target selections in total (9 conditions × 300 targets).

Throughput

Effective IDs were calculated for each trial using the standard deviation of the distance to the center of the selected target for each participant (see Equation 2). The mean effective throughput (TPe) for each condition can be seen in Figure 3. We conducted a two-way RM-ANOVA to determine if the Texture and Displacement of the virtual avatar hands had a significant influence on TPe in the Fitts' Task. Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated (all $p > .109$). We found no significant main effect of Displacement, $F(2, 35) = 1.053$, $p = .345$, and no effect of Texture, $F(2, 35) = .131$, $p = .877$, and no interaction effect of Displacement × Texture, $F(4, 140) = 1.647$, $p = .166$. As it is conceivable that the conditions were not performed equally well while repeating the task, we entered the trial order as independent variable and performed a three-way ANOVA, which showed a significant effect for trial order, $F(1, 271) = 50.21$, $p < .001$, however, not for the other factors and no interaction effect with the other factors (all with $p > .128$). Mean throughput between all conditions was 6.02 ($SD = 1.15$).

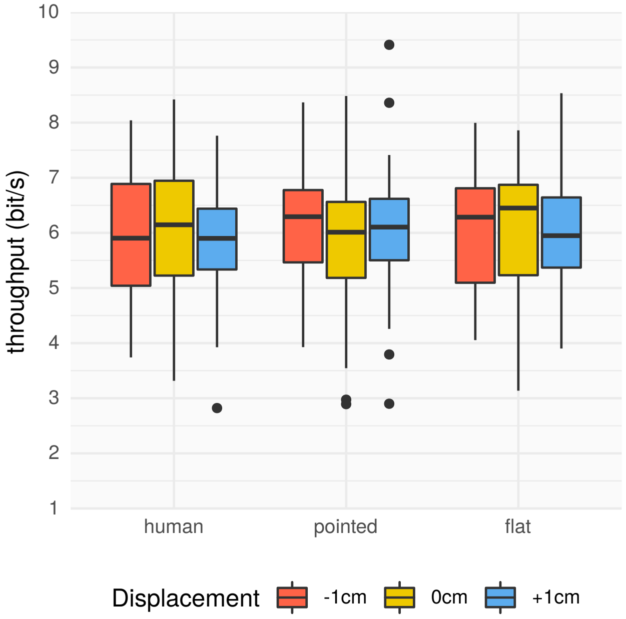

Figure 3: Boxplot of the effective throughput (TPe) for each condition. No significant effects were found.

As analyses of variance showed no effects on throughput, the data were examined using estimated Bayes factors and the Bayesian Information Criteria [49]. The anaylsis was conducted to determine wheather the fit of data under the hypothesis that no effects occurred under model subsets of Displacement, Texture, and Displacement × Texture is more likely. Participants were included as random factors. Estimated Bayes factors of Displacement were .060 (±0.86%), for Texture .042 (±1.67%), and for Displacement × Texture < .001 (±2.4%). Both main factors had an estimated Bayes factor of .002 (±2.53%). Thus, very low Bayes factors for all models suggest that the throughput data were in favor of the hypothesis that no effects occurred.

Mean Time

We analyzed the log-transformed mean time of each participant while performing a task using a two-way RM-ANOVA. As Mauchly's Test of Sphericity indicated that the assumption of sphericity has been violated for Displacement, $\chi^2(35) = .563$, $p = .039$, we applied Greenhouse correction to that factor. There was no significant main effects for Displacement, $F(2, .852) = .539$, $p = .558$, no effect of Texture, $F(2, 35) = .318$, $p = .729$, and no interaction effect of Displacement × Texture, $F(4, 140) = 1.031$, $p = .394$. Mean time between all conditions was 588 ms ($SD = 143$). Movement times related to ID can be found in Figure 4.

Bayesian factor analysis of the model subsets were in favor of rejecting the hypothesis that an effect occurred for Displacement .053 (±0.72%), for Texture .056 (±2.27%),

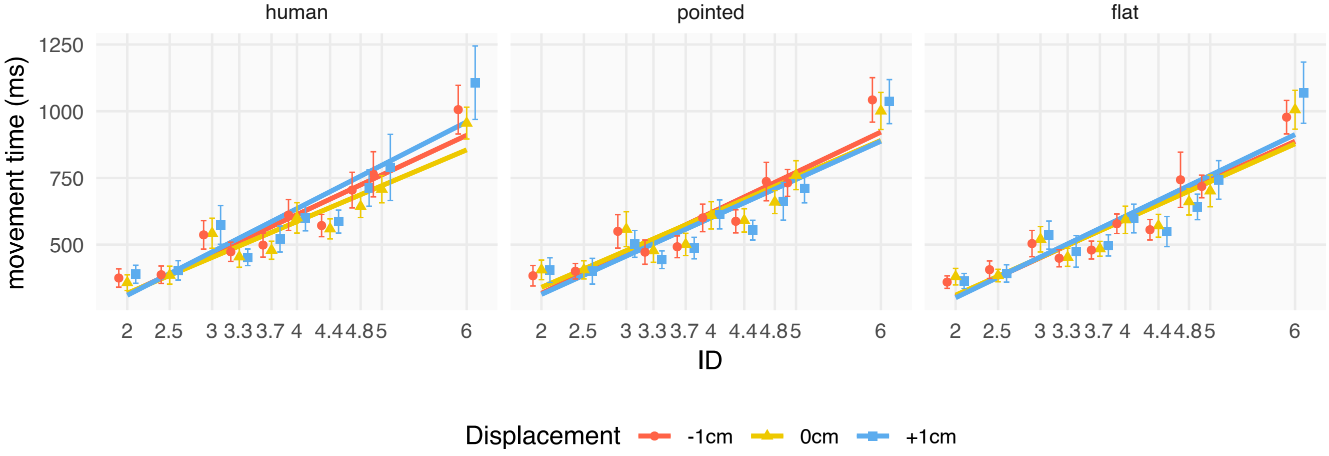

Figure 4: Function fit and movement time for all conditions and IDs.

and for DISPLACEMENT × TEXTURE < .001 (±2.01%). Both main factors had an estimated Bayes factor of .002 (±1.06%).

Error Rate

The ratio of valid and invalid hits per participant was used as error rate measure. As the error rate is nonparametrical data we used aligned rank transform (ARTools for R[1]) for multiple factors as suggested by Wobbrock et al. [50]. A two-way RM-ANOVA showed neither an effect of TEXTURE, $F(2, 280) = 2.526$, $p = .082$, nor DISPLACEMENT, $F(2, 280) = 2.131$, $p = .121$, and no interaction effect between both factors, $F(4, 280) = 1.442$, $p = .220$. Mean throughput between all conditions was 93.5% ($SD = .032$).

Accuracy

The average distance from target center to the coordinates of where the participant hit a target was used as accuracy measure. Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated ($all p > .51$). We found no significant effect of DISPLACEMENT, $F(2, 35) = .194$, $p = .824$, no effect of TEXTURE, $F(2, 35) = .276$, $p = .760$, and no interaction effect of DISPLACEMENT × TEXTURE, $F(4, 140) = .329$, $p = .858$.

Subjective Measures

Subjective impressions of each hand pairs were asked within the VR. As there is no standardized questionnaire of virtual limb-ownership, we analyzed individual items using nonparametric tests which is common practice within the related work [1, 23, 39]. For the individual items of the subjective questionnaire, we used the ARtool for aligned rank transformed data and multiple factors. For pairwise comparisons we performed Wilcoxon signed-rank tests using Bonferroni correction for p-value adjustments. Means and standard deviations of the subjective ratings are shown in Figure 5.

There was no significant main effect on Q1 ("I have the sensation to feel present in the virtual space") of DISPLACEMENT, $F(2, 280) = 2.036$, $p = .132$, however, not of TEXTURE, $F(2, 280) = 17.880$, $p < .001$, and no interaction effect of DISPLACEMENT × TEXTURE, $F(4, 280) = .585$, $p = .674$. Pairwise comparisons of the TEXTURE levels revealed a significant difference between the *human* and the *flat* ($p = .008$) as well as between the *pointed* and the *flat* hands ($p = .012$).

We found significant main effects on Q2 ("It seems like my own hands are located in the virtual world") of DISPLACEMENT, $F(2, 280) = 17.176$, $p < .001$, and of TEXTURE, $F(2, 280) = 6.799$, $p < .001$. No interaction effect was found, $F(4, 280) = 1.258$, $p = .287$. Pairwise comparisons of the DISPLACEMENT levels revealed a significant difference between the *-1cm* and the *0cm* ($p < .001$) as well as between the *0cm* and the *+1cm* hands ($p < .001$). Differences between the levels of TEXTURE were significant between *human* and *flat* ($p = .044$) and between pointed and flat ($p = .041$).

For Q3 ("I feel as if the hands in the virtual world are my own hands") there were significant main effects of DISPLACEMENT, $F(2, 280) = 11.203$, $p < .001$, and for TEXTURE, $F(2, 280) = 4.804$, $p = .009$, but there was no interaction effect, $F(4, 280) = .456$, $p = .768$. Pairwise comparisons revealed significant differences between the *-1cm* and *0cm* ($p < .001$) as well as between the *+1cm* and *0cm* ($p < .001$) levels of DISPLACEMENT. For TEXTURE none of the pairwise comparisons was significant despite the main effect.

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

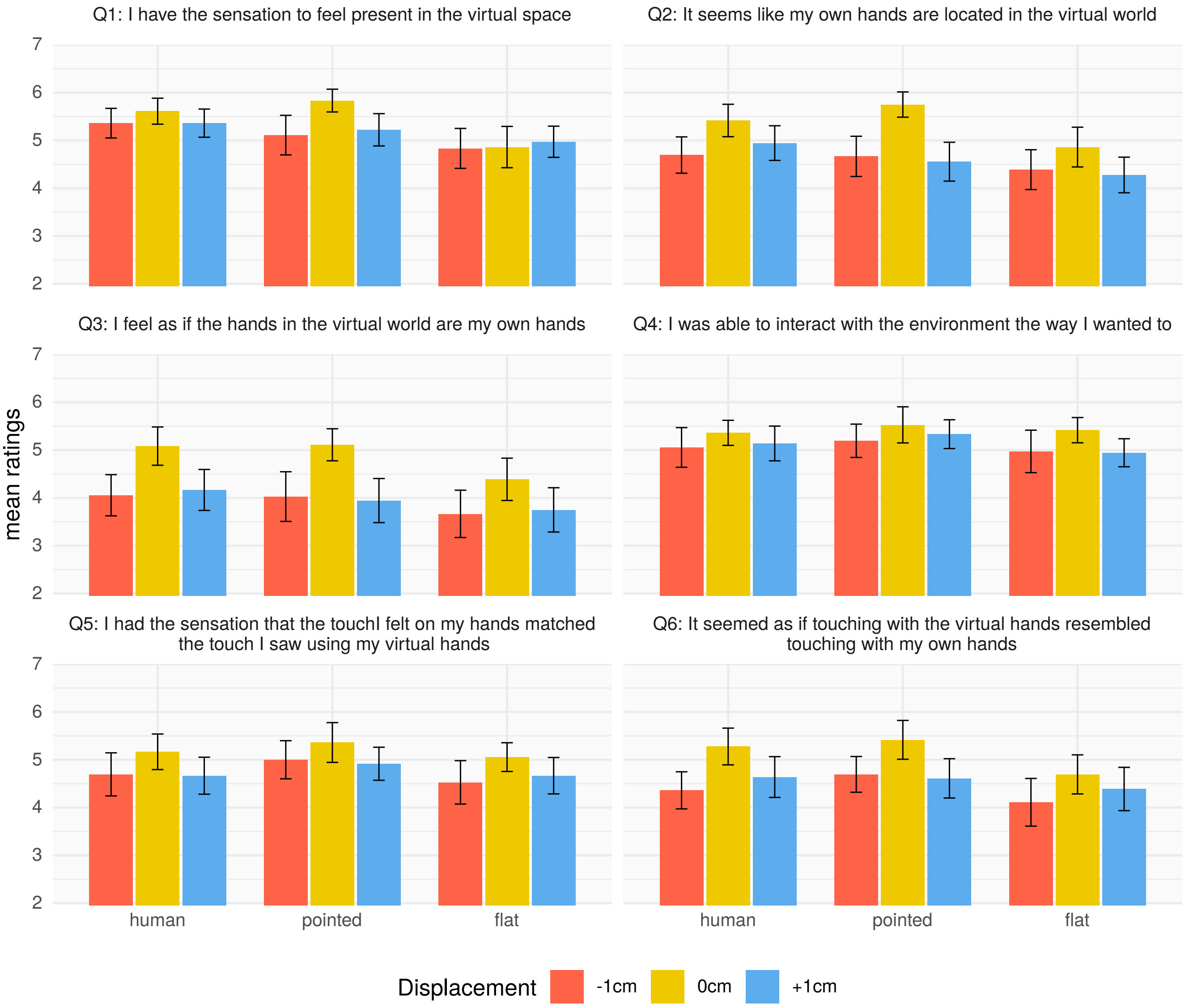

Figure 5: Subjective ratings of the six questionnaire items.

For Q4 ("I was able to interact with the environment the way I wanted to") there were significant main effects of Displacement, $F(2, 280) = 3.882$, $p = .022$, and for Texture, $F(2, 280) = 1.124$, $p = .326$, but there was no interaction effect, $F(4, 280) = .806$, $p = .522$. Pairwise comparisons revealed significant differences between the *-1cm* and *0cm* ($p < .001$) as well as between the *+1cm* and *0cm* ($p < .001$) levels of Displacement.

There was a significant main effect on Q5 ("I had the sensation that the touch I felt on my hands matched the touch I saw using my virtual hands") for Displacement, $F(2, 280) = 6.631$, $p = .002$, however, not on Texture, $F(2, 280) = 3.785$, $p = .024$, and there was no interaction effect, $F(4, 280) = .479$, $p = .751$. Pairwise comparisons revealed significant differences between the *0cm* and *+1cm* ($p < .011$) between the Displacement levels, however, could not show any significant differences between the levels of Texture.

For Q6 ("It seemed as if touching with the virtual hands resembled touching with my own hands") there were significant main effects of Displacement, $F(2, 280) = 10.954$, $p < .001$, and for Texture, $F(2, 280) = 3.714$, $p = .026$, but there was no interaction effect, $F(4, 280) = 1.250, p = .290$. Pairwise comparisons revealed significant differences between the *-1cm* and *0cm* ($p < .001$) as well as between the *+1cm* and *0cm* ($p = .006$) levels of Displacement. For Texture none of the pairwise comparisons was significant despite the main effect.

Performance and Experience

In order to understand if there is any relation between subjective and subjective experience measures, we performed a linear regression analysis with throughput as performance index and the questionnaire items as predictors. The regression equation was significant, $R^2 = .851, R^2_{Adj.} = .849, F(6, 317) = 303.8, p < .001$. The scatterplots (not illustrated) of standardized residuals indicated that the data met the assumptions of homogeneity of variance, linearity, and homoscedasticity. No auto-correlations were found. Table 1 lists all β-coefficients for each parameter. The highest and only significant predictor of performance was found in the ratings of item Q4. While R^2 indicates a good fit of the model, ratings in Q4 explain nearly 21.3% of the variance of the mean throughput.

5 DISCUSSION

In this study, we investigated the effects of geometry displacement and texture rendering on the average input performance in a 2D Fitts' law task in VR. Our results show that neither mean time, nor throughput, nor accuracy were affected while performing the task. We could not find any results providing evidence that changing depth cues of virtual avatar hands can increase or decrease a user's input performance in VR. We conclude that participants did not integrate the virtual hands differently even when different depth cues via textural or geometrical changes of their virtual appearance were presented. As expected, subjective experience of body ownership was affected, however, only subjective ratings of perceived motor control seem to correlate with the objective throughput measure, which indicates that only the perceived ability to interact with the virtual world in an intended manner can potentially affect performance.

For understanding visual-haptic integration this finding is decisive, as the proprioceptive system and coordinated control of eye and hand movement seem not to require all depth cues of the own body. Instead, providing a more (or less) reliable (or plausible) appearance of the own body is being ignored and does not seem to correlate to the degree of perceived limb ownership or presence. As the task must be performed using visual feedback, we assume that any visual cues following the own body movement can be utilized to perform the task. This explains why external devices (such as pens and sticks) and even referential devices (such as mouse cursors) deliver high throughput rates [15, 26, 31]. While such devices are rather extensions of the own body and not integrated into one's own body scheme they do not necessarily require a certain appearance that supports depth cues. Controlling the proprioceptive system using binocular vision to estimate the location of the referential device seems to be sufficient to perform the task. We assume that the appearance is being ignored as long as it does not interfere with the task (such as in cases of latency). There are multiple explanations why depth cues of the own body had no effect in our experiment:

(1) The level of virtual body ownership does not affect spatial localization, but spatial localization can affect body ownership while both require synchronous vision and haptics. In line with previous work, there is no direct relationship between the *who* and the *where* of a virtual embodiment. Even significant changes of depth cues – as presented in our experiment – do not affect spatial localization and, thus, performance as long as congruent body tracking and rendering are warranted. Using regression analyzes we showed that participants stated that they felt that the [29] interaction with the environment was better, when they performed better. From this point, we can assume that performance can affect the level of embodiment, which is in line with Slater et al. [42], who suggest that performance is not affected by the feeling of being immersed but vice versa. This is also in line with previous work showing that delays or asynchronous movements affect performance, and thus, the illusion of body ownership [20, 28, 40]. As high levels of self-location were always provided in our experiment, it is conceivable that the appearance of the embodiment does not affect performance and only the perceived performance in completing a task affects the level of embodiment.

(2) Geometrical and textural depth cues of the own body are not integral parts of spatial localization. This is not fully in line with previous work, where missing or conflicting depth cues such as transparent hands had an effect on the performance in a Fitts' task [28]. However, Knierim et al. [20] found no effect in typing performance between hands with 50% and 0% transparency, which also shows that any plausible visual feedback where users can determine the own body movement provides a consistent level of motor control and, thus, performance. Compared to other experiments with effective throughput measures [12, 22, 27, 28] the average throughput ($M = 6.02, SD = 1.15$) in the herein presented experiment is quite high, which indicates that the participants were able to interact in the desired way throughout all conditions.

Table 1: Standardized regression coefficients correlating with throughput as outcome variable.

#	Concept	Question	β	SD	p	sig.
Q1	Presence	I have the sensation to feel present in the virtual space	0.106	0.075	0.160	
Q2	Virtual Limb-Ownership	It seems like my own hands are located in the virtual world	-0.003	0.094	0.976	
Q3	Virtual Limb-Ownership	I feel as if the hands in the virtual world are my own hands	0.038	0.084	0.649	
Q4	Control	I was able to interact with the environment the way I wanted to	0.213	0.083	0.011	*
Q5	Touch Sensation	I had the sensation that the touch I felt on my hands matched the touch I saw using my virtual hands	0.123	0.097	0.204	
Q6	Touch Realism	It seemed as if touching with the virtual hands resembled touching with my own hands	-0.135	0.087	0.122	

(3) The presented stimuli were not sufficient to elicit an effect. While all depth cues using the flat shaded hand avatar have been reduced, the position of the own body can still be determined by stereoscopic vision or the anticipated shape of the own body. However, using the pointed hand with high equipped with high-contrasted depth cues showed no improvement despite the high-contrast informative cues of the actual body position. An increase of spatial localization and a reduction due to the lack of body ownership using pointed hands is to be considered as unlikely (but not impossible) as both effects need similar effect sizes in order to cancel each other out.

(4) The Fitts' task testing the performance of virtual avatar hands with fine granular and repetitive movements does not make it possible to detect differences in performance. As the input pattern of the task remains constant, participants quickly learned the movement they had to perform in order to select the next target resulting in a motor control delegated cycle by muscle memory only. As we found no interaction effects of our factors with the sequence of trials, we conclude that proprioceptive control equally grows while performing the task.

The first point would indicate that spatial localization and body ownership are mainly independent processes but rely on congruent vision and haptics. As already shown by Della Getta et al. [7] the level of virtual body ownership does not necessarily correlate with performance. It is conceivable that target selection according to Fitts' model is not necessarily meaningful due to the repetitive nature of the task. Nevertheless, due to the high sensitivity of the test, we consider this possibility to be low. As the experiment by Mason et al. [28] has shown, lacking depth cues a definitely reduce throughput in a Fitts' law task. However, toon-shaded hands without any depth information were just as sufficient for the participants in our study to perform the task as using hands with high contrast patterns, which indicates that spatial localization was ensured. The fact that, according to earlier work [7, 20, 29, 39], the subjective experience of body ownership was influenced, but the objective performance not (in systematic manner), indicates that the body awareness and spatial localization are two different processes, both based on the assumption that the visual-haptic integration creates a unified percept. This is still in line with the paradigm of optimal cue combination as a bottom-up process, however, would indicate that body ownership is a top-down process – a sense and feeling of body awareness about the actual *who* of the visual embodiment.

Limitations and Future Work

This work faces a number of limitations, which mainly touch the question of generalization of our results and must be addressed in future work. The information transmission from a human to the computer system considering psycho-motor control comprises a limited view on measures of input performance or behavioral changes while experiencing avatar hands with varying depth cues in VR. Furthermore, the repetitive nature of the task prevents us from drawing clear conclusions about interaction strategies in real use cases. Thus, non-repetitive tasks could be used to counter potential effects of learning and muscle memory. However, to learn if self-location is really the only important sense of embodiment for an optimal performance in a Fitts' Task, transparent or low-contrast avatar hands could be investigated in a similar setup.

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