A Model of Limb-Ownership

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Figure 1: Levels of contrast used in the Virtual Environment, exemplary on the realistic hand. The contrast values are 1.5%, 2.5%, 3.5%, 4.5%, 5.5% from left to right.

ABSTRACT

The sense of limb and body ownership in virtual reality (VR) is assumed to be subjectively measurable by questionnaires, which suggest that avatars that are close to reality result in a high sense of limb ownership. Several attempts at measuring the level of limb ownership in an objective manner have been proposed by recent studies. At the same time, finding the just noticeable difference (JND) for different tactile and similar senses have been shown to be an indicator for the level of limb ownership. We aim to test the hypothesis that using a JND measure is an objective measurement for limb ownership in VR. We also researched if different levels of visual noise, as well as hand appearance impact the sense of limb ownership in virtual reality. Sixteen participants completed a two alternative forced choice weight discrimination task with 30 conditions in a mixed design study. We found that weight perception is not suited as measure for limb ownership. However, using a VR had an influence on the ability of weight discrimination.

1 INTRODUCTION

Recent advances in virtual reality technology enables people to be part of highly immersive experiences in various digital environments. Moreover VR allows its users to take on and have control over entire bodies. Commonly presence, the feeling of 'being' in VR [30], is induced via visual and auditory stimuli. Previous work has shown that those impressions should be properly aligned with real stimuli to induce the illusion of virtual body ownership [16, 35]. Multi-modal integration is currently believed to be the reason for any sense of ownership[4, 36]. When multiple, matching sensory signals (e.g. visual, temporal & spatial) are received from a limb, ownership is induced.

This assumption has been confirmed during the rubber hand illusion (RHI) experiment by Botvinick and Cohen [5]. In this experiment, a rubber hand is placed on a table in front of a participant. The participant's real hand however is hidden from his/her view behind a small wall. Now, both real and rubber hand are touched on the same spot. After only a short period of time, the majority of participants began to perceive the touched location to be on the rubber hand instead of their own hand a few centimetres away. This effect is now commonly referred to as *proprioceptive drift*. Botvinick and Cohen [5] developed a qualitative body ownership questionnaire, which is now commonly used to measure perceived ownership qualitatively (c.f. [19, 27]. Since then numerous follow-up studies assumed a connection between spatial localisation and limb ownership (c.f. [12, 18]).

However, recent research has cast doubt on this assumption. During their experiment Rohde et al. [27] did not only measure proprioceptive drift during synchronous but also during asynchronous stroking, the most common control condition used during the

RHI. However body ownership is only perceived in their synchronous condition, indicating two different mental mechanisms.
While initially interested in how multi sensory information processing develops by inducing the RHI in young children and adults, Cowie et al. [7] observed a different development between visual-tactile and visual-proprioceptive processing. Children are able to experience the illusion induced by visual-tactile stimulation, but reported a greater proprioceptive drift. This indicates two different mechanisms developing, with the visual-tactile one being developed at an age of at least four years. Additionally embodiment was only related to this visual-tactile process.
Abdulkarim and Ehrsson [1] artificially changed the participant's hand position during the experiment, without him/her noticing. This manipulation however, did not change the strength of the rubber hand illusion. Thus, the illusion seems to be independent of changes in hand position sense which also indicates separate processes.
Recently [23] developed a mathematical (maximum-likelihood estimation) model to predict the perceived location of a participant's hand in the RHI. However this model was only able to predict localisation and not ownership, which seems to be systematically different. This should not be the case if the processing pathway is shared. In contrast Samad et al. [29] developed a Bayesian causal inference model for experienced ownership. Having found two different mathematical models further indicates a clear separation between localisation and ownership.

We investigated weight perception as a way to quantitatively measure limb ownership specifically. We believe it is important to investigate possible alternative measures for body ownership to better understand the complex process of embodiment, as its understanding could help to further improve the immersion of systems. Instead of spatial localisation, we decided to use the ability to distinguish between two weights as measure of limb ownership, as weight perception is known to be an integral part of human sensory [8, 26, 28]. Additionally we believe that, since weight discrimination is a multi sensory heavy task [2], it is able to induce body ownership illusion.

We present the results of a psychophyscial experiment examining the impact of hand appearance and visibility on the ability to distinguish weights inside a virtual reality environment in order to determine whether latter is suitable as measurement for limb ownership. We hypothesised that the more human-like virtual hands are the greater the ownership and therefore worse weight discrimination performance. We also assumed the lesser visible the virtual hand is the better is weight discrimination performance. With less visual cue, haptic sensory information should be weighted as more important, resulting in better performance overall. We tested this by determining the just noticeable difference between two weights. Our results show that neither contrast nor the type of hand had any effect on the success rate. However, we found that when using an abstract hand task completion time was significantly faster.

2 RELATED WORK

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

2.1 The Rubber Hand Illusion

The RHI experiment by Botvinick and Cohen [5] is a special case of visual-haptic integration. Through simultaneous stroking of one's real and an artificial limb one can be tricked into perceiving the fake limb as their own - replacing it during the illusion.
For this deception to appear delusional sensory impressions have to be (time-)congruent as well as somewhat realistic resulting in a smaller effect observed when using non human-like fake limbs [6]. While originally shown only for passive stimuli an illusion can also be perceived without any tactile stimulation only with correlated fake limb movement [16]. Furthermore Kalckert and Ehrsson [17] found different combinations of sensory input to also induced the illusion.

However in more recent studies the connection between spatial limb localisation and ownership has been scrutinised [23, 27]. Both studies indicate a clear separation between body localisation and ownership. After those findings it is again unclear how to measure limb ownership quantitatively. Recent research already tried to find a new way to measure limb ownership but was not yet successful (e.g [33]).

2.2 Virtual Body Perception

The RHI also has been shown multiple times to be experienced inside virtual reality [14, 18, 38]. Similar to its counterpart, the virtual arm (hand) illusion (VHI) [34] also depends on human-likeness of the virtual hand [20, 38]. Slater et al. [35] also showed there is no need of any haptic stimulus needed to induce the VHI analogous to effects monitored for the RHI. Synchronous visual and proprioceptive sensory information seems to be sufficient. Various other studies have explored how changes in virtual avatar appearance influences (limb-)ownership. Schwind et al. [31, 32] for example observed an effect on presence felt based on gender and number of fingers. Peck et al. [25] monitored a reduction of racial bias after having fair-skinned people using a dark-skinned avatar. Kilteni et al. [19] even successfully investigated whether implausible virtual limbs can be integrated into one's body scheme to an extent. Unfortunately ownership in virtual reality currently still depends on the initial localisation-ownership assumption made by Botvinick and Cohen [5].

2.3 Weight perception

In 1834 Weber [37] developed the concept of difference threshold or just noticable difference (JND) by conducting an weight comparison experiment. Participants needed to judge whether a standard or an comparison weight was heavier. He found the JND was dependent upon the reference weight and was a constant fraction. Later on Fechner [9] transformed those observations into two mathematical laws - also known as the Weber-Fechner law. Weber's law is a mathematical description of Weber [37]'s observation and commonly expressed as Weber Fraction $k = \frac{JND}{S}$ (with S being the reference/base stimulus - e.g. a weight of 200 grams). This fraction is different for each type of stimulus - in his own experiment for example Weber [37] observed a fraction of about 0.1 (or 10%). In contrast to Weber's law, Fechner's law assumes a logarithmic relationship between stimulus and perception. With k

being a constant based on the stimulus type (e.g. visual or haptic).

$$p = k \cdot \log \frac{JND}{S} \tag{1}$$

While Fechner's law is mainly used for brightness or loudness perception, Weber's law is commonly used in context of weight perception measurement (c.f. [10, 28]). We therefore use the Weber Fraction throughout this work to measure performance. With the predominant way of measuring limb ownership being heavily questioned in recent research we propose a new way of measuring ownership quantitatively. Instead of measuring perceptual drift we aim to measure the change in the Weber Fraction. We expect a worse performance during higher embodiment as well as contrast because of additional sensory information processing needed.

3 METHODOLOGY

In the following section, we provide an overview about our methodology. We explain how we have chosen our weights, describe our experimental setup, which tasks we used and exactly how and what we measured during our experiment.

3.1 Weight interval determination

While the Weber Fraction's magnitude is generally quite well known to be about 10% in optimal environments, little is known about how virtual environments and other external factors influence it. For this reason we decided to conduct a psychological pre-study to determine reasonable weight intervals for our main study. Three volunteers (which did not participate on in the main study later on) needed to distinguish between weights in virtual reality (three males: $\bar{x} = 24.33$ years ($\sigma = 1.55$)). We used the same experimental setup as described later for our main study, but only used the non-realistic hand with minimal contrast. We use this setup to minimise interference introduced by embodiment (c.f. [20, 38]) and visual hand appearance (c.f. [23]) and should therefore represent the most optimal scenario. Furthermore no participant had to answer any question related to body ownership etc. as they are not relevant for our pre-study. Each participants task was to determine his/her threshold to distinguish a reference weight (185 grams) every single time from an other, heavier weight. The mean threshold was a weight of 215 grams (we raised the weight in five gram intervals) According to those findings we decided to use an interval of ten grams between each weight. We therefore end up with 185, 195, 205, 215, 225, 235 and 245 grams with 185 being our reference weight.

3.2 Study design

We conducted a psycho-physical experiment using the independent within-subject variables contrast (five levels) and Weight Difference (six levels) as well as Hand (two levels) as between-subject variable. In a two alternative forced choice (2AFC) task each individuals needed to determine which weight presented was heavier. Our measures are *weight left*, *weight right*, *chosen weight* (left/right), *correct response* and *response time*. Additionally we measured 16 questionnaire items about embodiment.

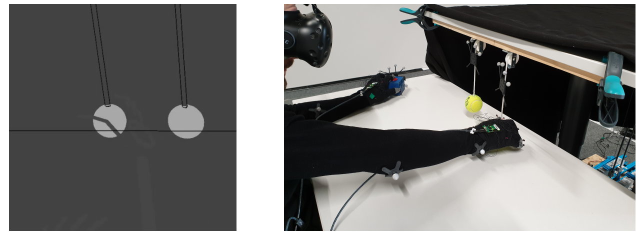

Figure 2: (a) Image of the virtual environment presented, (b) image of participant interacting with the real world object.

3.3 Hand & Contrast conditions

We used two different types of hands to investigate the impact of human-likeness on perceived limb ownership. One group of participants used a *human* hand which is similar to a real, androgynous hand. This model was used to eliminate specific gender cues of human hands, which can cause distractions and uncomfortable feelings in VR [31, 32]. The others used a minimalist, *abstract* hand. With three bone segments per finger, a ring as palm and a straight bone segment as the forearm. Both models have been provided by Schwind et al. [33] and use the same skeleton rig with equal degrees of freedom.

We manipulated the contrast of both hands to adjust the amount of visual noise present. We used the same five levels (*1.5%, 2.5%, 3.5%, 4.5%, 5.5%*) and base colour (hex code: #404040) as reported by Matsumiya [23]. We however did not use a shader at all to minimise colour variation.

3.4 Task and Stimuli

In a 2AFC task participants needed to determine which one of the two presented weights was heavier. To do so they had to pull on two ropes with those attached. However, participants were allowed to pull each rope only once per trial. Everyone had to use their strong, right hand to pull - the order was not predetermined. Afterwards, participants communicated their decision by pressing a corresponding button (right button = right weight heavier, left button = left weight heavier).

The visual stimuli consisted of a minimal virtual environment. It was completely devoid of colour and used only varying degrees of grey. All objects that were not directly used for completion of the given tasks but still interacted with in the real world were of the same grey base colour with a black outline. These objects were the chair that participants were seated on, the desk in front of them, and the box on which the buttons had been placed in the real world. The background was also completely grey but without any outlines. In contrary to that, the spheres, which were the object participants had to interact with, were of a lighter colour (hex code: #AAAAAA). Just like [23], we did this to make sure participants had a clear visual clue where the relevant stimulus is located. At the same time, the hands in virtual environment used different and varying levels of contrast, depending on the trial. Those levels correspond to our Contrast factor.

While visual stimuli were controlled through the virtual environment, tactile stimuli are perceived through real world interactions. We have chosen tennis balls to facilitate pulling, as they have a comfortable holding size of 6.6 centimetres in diameter. Both buttons were embedded inside a wooden, self-made casing. We used two nylon buttons by Bao Lian[1]. The effective weight when pulling down the tennis balls was one of those reported in 3.1, with one of them always being the reference stimuli of 185g, and the other either 195g, 205g, 215g, 225g, 235g or 245g.

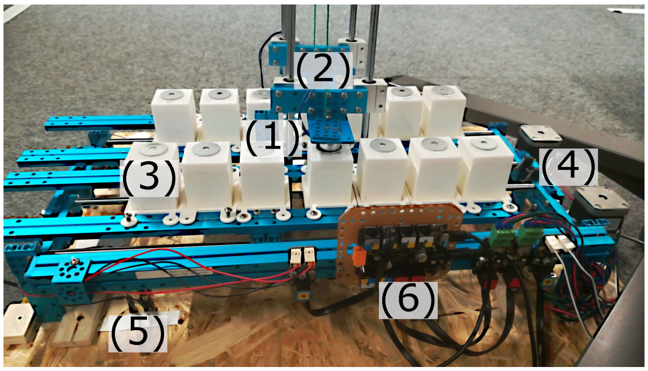

Figure 3: Image of the robot. The labelled components are (1) solenoid, (2) vertical guiding rail, (3) 3D printed cuboid, (4) stepper motors, (5) transistor for switching, (6) Makeblock Orion.

3.5 Apparatus

We used the motion capturing system OptiTrack in conjunction with self-made active-marker tracking gloves, a wireless version of the head-mounted display (HMD) HTC Vive, as well as a modified robot building kit for stimuli arrangement. The virtual environment was developed in C++ using a modified version of the Unreal Engine (v. 4.23.1[2]) by Epic Games.

The OptiTrack system we used for marker tracking consisted of twelve cameras (8 Prime 13W and 4 Prime 13 running at 240 fps) placed in a room with 3.8m width and 4m length and 2.5m height. Movement of both hands was detected by Motive (Version 2.1.1 final) and streamed to Unreal Engine (UE). Movements were transformed into virtual space by the newest Unreal Engine Plugin (Version 1.2.3) made by OptiTrack. Motive's built-in skeleton assets for left and right hands were used to tracked our self-made gloves.

This glove pair was built to mimic OptiTrack's official glove prototype[3] and made out of thin, elastic polyester. Each glove had nine active infrared markers with one additional passive marker attached to the outer wrist, one on the inner forearm and one on the elbow of the participant. To match the tracking space of hands and rigid bodies with the tracking space of the HTC Vive, we used rigid body markers on top of the HMD and the Optitrack's OpenVR driver (Version 2.0.0), which enables streaming tracking data of the head-mounted display into SteamVR.

We modified a "XY Plotter Robot Kit" by makeblock[4] to automatically change and provide the desired weights for each trial. Our UE application sent commands via serial connection to an Makeblock Orion, which controls two stepper motors and two holding solenoids[5] via a IRLZ34N[6]. Whenever the participant pressed one of the two buttons the Makeblock Orion sent a message back to UE.

We used two stepper motors to drive two rails on which our weights were placed. The high precision of stepper motors allows us to move these weights on predetermined positions. In order to minimise possible bias that might occur when participants "hear" whether a particular rail was moved, we ensured that both rails were always moved and additionally got them a pair of in-ear headphones.

The solenoids were attached to a vertical guiding rail construction with ball bearings. One was able to pull up the solenoids by pulling down the tennis balls mentioned in 3.4 due to both being attached to each other through a tackle consisting of four pulleys and two ropes. When the stepper motors communicated to the Makeblock Orion that they had finished their movement, the solenoids were turned on, connecting the weights to the tackle. This construction was used to completely eliminate any effect which the form and shape of the weights in virtual reality and the tactile feedback of the real objects might have. To ensure that the system works all the time and is not susceptible to uncontrollable swinging of the hooks, we added the guiding rails to restrict the movement of exchangeable weights and solenoids to vertical direction only. A tennis ball has weight between 56.0g to 59.4g [15]. In our case, their weight was 57.5 ± 0.3g. Rigidbody markers on the ropes added another weight of 15/±0.01g. This sums up to a total counterweight of 72.5g. The magnetic solenoids and guiding rail mounting have a combined weight of 180g. We then calculated the actual weight needed to be picked up by the solenoids to achieve our target weight. We filled sealable, 3D-printed cuboids with a length and width of 4cm, and a height of 5cm with weights of 28 ± 1g. This results in a filling weight of 77.5g for the reference weight. To make sure our calculations were right, we used a newton meter and found our error to be below 3g.

In VR we modelled the front part of the tackle construction - the tennis balls and the ropes attached to them - and placed them in the virtual environment in accordance to their real world position. This was done by attaching rigidbody markers to the ropes. Similarly, we attached markers to the wooden casing of the buttons, which allowed users to place the box themselves.

Unfortunately the Unreal Engine currently does not support outlines on cable components [7], which we used to represent our ropes, so we fixed it by adding *Result.bRenderCustomDepth = ShouldRenderCustomDepth();* to *CableComponent.cpp* and compiled the engine ourselves.

3.6 Measures

We measured the just noticeable differences of the weight stimuli, correctness of the button press and the response times of the participants during the experiment. After each experiment we presented a modified version of the survey by Gonzalez-Franco and

[1]https://en.bao-lian.com/?p=4808
[2]https://github.com/EpicGames/UnrealEngine/releases/tag/4.23.1-release
[3]https://v22.wiki.optitrack.com/images/3/34/ActiveFinger_Prototype.jpg
[4]https://www.makeblock.com/project/xy-plotter-robot-kit
[5]https://www.red-magnetics.com/en/product-groups/electromagnets/electromagnets/its-ms-2015
[6]http://www.irf.com/product-info/datasheets/data/irlz34n.pdfMOSFET
[7]https://issues.unrealengine.com/issue/UE-34365

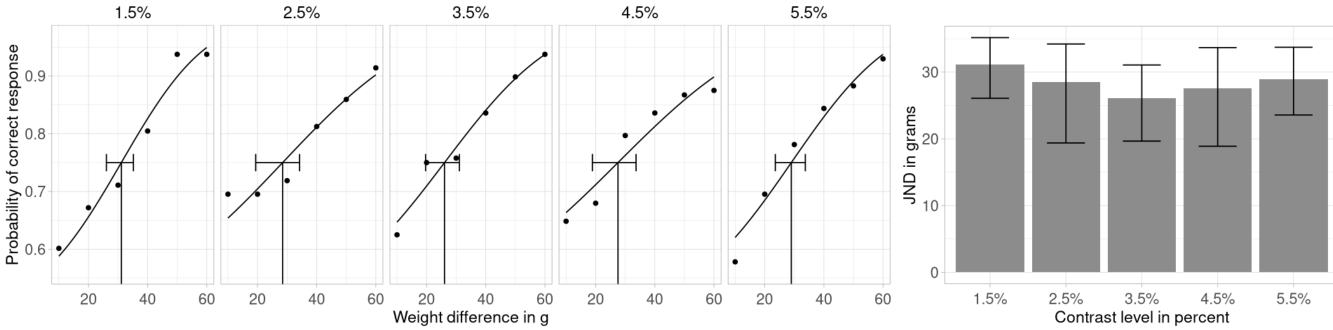

Figure 4: Psychometric data and thresholds of JND. Error bars show the 95% confidence interval.

Peck [12]. We removed the section 'external stimuli' completely as well as Q3, Q4, Q5 & Q20 because they did not fit our experimental setup. Additionally we asked the participant which type of hand they just used throughout the experiment (abstract or realistic), whether they already had experience with VR and provided a way to supply qualitative feedback.

3.7 Procedure

After a short introduction to the general procedure of the study and signing a letter of consent, the participants sat down on a chair and were asked to put on the active marker gloves, passive arm markers, Bluetooth in-ear headphones to eliminate external noises and the HMD. To familiarise with the equipment and the virtual reality environment, the participants were asked to perform simple tasks like spreading their fingers, grabbing the tennis balls and the wooden casing of the buttons and pressing the buttons. Once the participants were ready and used to the setup the main study started. The participants could request a short break at any time if the experiment became physically or mentally exhausting.

We used a 30 x 30 balanced Latin Square to counterbalance all conditions. In each condition the user was presented with two weights and had to pick the heavier weight. We randomised on which side the reference weight was. The participant had to pull each rope separately with the right hand once and press the button corresponding to the heavier weight. After the button press a new weight pair was prepared. The participant was signalised with a sound when the next trial started. Every condition was repeated eight times, which resulted in 240 trials per participant. After the main experiment ended, every attendee had one minute of exploration time with the highest contrast level to ensure minimum embodiment variation (similar to [23]). Afterwards each attendee had to fill in a questionnaire and could give feedback in an short unstructured interview. The complete procedure took approximately one hour and fifteen minutes.

3.8 Participants

Sixteen voluntary participants (11 male, 5 female) took part in our experiment. The mean age of the participants was 24.25 years ($\sigma = 2.29$). All participants were right handed. Two participants reported that they had never use any VR setup before, while all other said they do not use it regularly, but have used it at least once before. The people were gathered through a university intern mailing list, social media and word of mouth. One participant desired a short break. Informed consent was obtained from each participant prior to the experiment.

4 RESULTS

All of the data captured and analysed as part of this experiment is publicly available on our Github repository [8] under the MIT license. We also provided a short demonstration video there.

4.1 Data Analysis

We fit psychometric data with a cumulative normal function (assuming a 0% lapse rate) using the quickpsy R package by Linares and López-Moliner [21]. We fitted a maximum-likelihood model and used a 75% threshold as our measure of a just noticeable difference assuming a base guessing rate of 50%. We also used nonparametric bootstrapping with 1000 trials each to estimate the 95% confidence intervals. Finally, we did also calculate individual JND's for each contrast level with 100 trials of non-parametric bootstrapping (see figure 4). Within those we replaced impossible threshold values (e.g. -215.85g) with the median of the corresponding condition. Each value above 60g or below 0g was therefore replaced.

After each session, participants were asked to fill in our modified questionnaire by Gonzalez-Franco and Peck [12], as described in section 3.6. These questions have been used repeatedly to rate different aspects of embodiment [11, 22, 24]. Each item could be rated on a seven point Likert scale between *strongly disagrees* (-3) and *strongly agree* (+3) (see Table 1, Q1 - Q19). We added one additional question (Table 1, under HQ) to check whether participants perceived their and as realistic or abstract. Qualitative feedback was analysed by comparing notes from all researchers present at each session, at least two were present at all times, and from an open-ended final question inside the questionnaire.

4.2 Quantitative Measures

All individual JNDs were entered into a one-way repeated measures analysis of variance (RM-ANOVA) with the within-subject factor Contrast. There was no significant effect of Contrast

[8] https://github.com/phHartl/model-of-limbownership

ID	Questionnaire Item	Concept	Abstract	Realistic	Combined
Q1	I felt as if the virtual hand was my hand	Body ownership	1.50±1.31	0.50±1.41	1.00±1.41
Q2	It felt as if the virtual hand I saw was someone else's	Body ownership	-2.63±0.52	-2.25±0.71	-2.44±0.63
Q6	It felt like I could control the virtual hand as if it was my own hand	Agency and motor control	1.88±1.36	1.50±1.07	1.69±1.20
Q7	The movements of the virtual hand were caused by my movements	Agency and motor control	2.25±0.89	2.13±0.64	2.19±0.75
Q8	I felt as if the movements of the virtual hand were influencing my own movements	Agency and motor control	-1.38±2.07	-0.88±1.46	-1.13±1.75
Q9	I felt as if the virtual hand was moving by itself	Agency and motor control	-1.88±0.99	-1.63±1.06	-1.75±1.00
Q10	It seemed as if I felt the touch of the hand in the location where I saw the virtual hand touched	Tactile sensations	1.13±0.83	0.63±1.69	0.88±1.31
Q11	It seemed as if the touch I felt was located somewhere between my physical hand and the virtual hand	Tactile sensations	-0.63±1.77	-1.38±1.92	-1.00±1.83
Q12	It seemed as if the touch I felt was caused by the ball touching the virtual hand	Tactile sensations	0.13±2.30	-0.75±2.12	-0.31±2.18
Q13	It seemed as if my hand was touching the ball	Tactile sensations	2.00±0.76	1.75±1.67	1.88±1.26
Q14	I felt as if my hand was located where I saw the virtual hand	Location of the body	1.88±0.64	1.88±1.46	1.88±1.09
Q15	I felt out of my body	Location of the body	-1.88±0.83	-1.88±1.89	-1.88±1.41
Q16	I felt as if my (real) hand were drifting toward the virtual hand or as if the virtual hand were drifting toward my (real) hand	Location of the body	-2.38±1.06	-1.63±1.85	-2.00±1.51
Q17	It felt as if my (real) hand were turning into an 'avatar' hand	External appearance	0.13±1.25	-0.38±2.13	-0.13±1.71
Q18	At some point it felt as if my real hand was starting to take on the posture or shape of the virtual hand that I saw	External appearance	-1.00±2.07	-1.00±2.00	-1.00±1.97
Q19	At some point it felt that the virtual hand resembled my own (real) hand, in terms of shape, skin tone or other visual features.	External appearance	-1.63±2.13	-1.38±1.41	-1.50±1.75
HQ	Which hand was presented to you? (abstract|realistic)	Hand appearance	8|0	5|3	13|3

Table 1: Questionnaire results. Omitted were Q3, Q4, Q5 and Q20 as they are not relevant to our survey. A Mann–Whitney U test was used on both the sums and individual embodiment scores.

$F(4, 60) = 1.358, p = .259, \eta^2 = .500$. Furthermore all individual JNDs were entered into a multi-factorial mixed-design ANOVA with the within-subject factor Contrast and the between-subject factor Hand. There were no main effects of Hand $F(1, 14) = .143, p = .711, \eta^2 = .004$, Contrast $F(4, 56) = 1.358, p = .262, \eta^2 = .050$ and Hand $\times$ Contrast $F(4, 56) = .936, p = .450, \eta^2 = .037$. Likewise we conducted a RM-ANOVA for response time with within-subject factor Contrast. There was no significant effect of Contrast $F(4, 60) = .490, p = .664, \eta^2 = .002$ with Greenhouse-Geisser sphericity [13] correction applied for the p-Value either. Just as with individual JNDs we also conducted a multi-factorial mixed-design ANOVA with the within-subject factor Contrast and the between-subject factor Hand for participants response time. There were no main effects of Hand $F(1, 14) = .514, p = .485, \eta^2 = .034$, Contrast $F(4, 56) = .511, p = .638, \eta^2 = .002$ and Hand $\times$ Contrast $F(4, 56) = 1.656, p = .202, \eta^2 = .006$, with Greenhouse-Geisser sphericity correction applied.

We adapted the formula of [12] to account for our modified questionnaire (see equation 2).

$$
\begin{aligned}
\text{Total Embodiment} = \Bigg(& \left(\frac{\text{Ownership}}{2}\right) \cdot 2 \\
& + \left(\frac{\text{Agency}}{4}\right) \cdot 2 \\
& + \left(\frac{\text{Tactile Sensation}}{4}\right) \\
& + \left(\frac{\text{Location}}{3}\right) \cdot 2 \\
& + \left(\frac{\text{Appearance}}{3}\right)\Bigg) \cdot \frac{1}{8}
\end{aligned}
\tag{2}
$$

We adapted for omitted questions from each sub concept calculation. Mann-Whitney U tests were used to detect significant differences of those subjective ratings indicating virtual embodiment. Figure 5 shows their distribution and corresponding test statistics. There was no significant difference on any concept between Hands. All questionnaire items, their mean value as well as standard deviation are reported in table 1. Additionally we calculated individual JNDs via our Hand factor. This distribution can be seen below in equation 3.

$$
\begin{aligned}
min_{JND} &= 12.31 \\
q_{0.25} &= 23.60 \\
\tilde{JND} &= 28.96 \\
q_{0.75} &= 35.07 \\
max_{JND} &= 45.62
\end{aligned}
\tag{3}
$$

Finally we conducted a two-sided, independent t-test to see if there is a significant effect of Hand on response time $t(2956.1) = -5.743, p < .001$, followed by a one-sided, independent t-test with alternative hypothesis being that response time with *abstract* is smaller than with *realistic*. This test resulted in a highly significant result of $t(2956.1) = -5.743, p < .001$. Contrary to Matsumiya [23] we found no trend in coefficients of variation (CV) (see equation 4) for each contrast level.

$$
\begin{aligned}
& CV_{1.5\%} = 0.33, CV_{2.5\%} = 0.40, \\
& CV_{3.5\%} = 0.32, CV_{4.5\%} = 0.51, \\
& CV_{5.5\%} = 0.40
\end{aligned}
\tag{4}
$$

4.3 Qualitative Feedback

After finishing all trials and taking off the HMD and tracking equipment, all participants stated that they felt physically and mentally fine. Still, three participants complained about the duration and monotony of the study. Three participants commented on unnatural finger or hand positions occuring for fractions of a second sometimes.

One person mentioned a "sweet spot" contrast level which leads the greatest self-confidence in the virtual environment (P7). This contrast level changes over the time of the experiment. At the start of the experiment a higher contrast level was preferred, in the later stages a lower contrast level was preferred by the participant.

5 DISCUSSION

The data of our psycho-psychical experiment with 16 participants showed no significant effect of limb appearance or contrast on

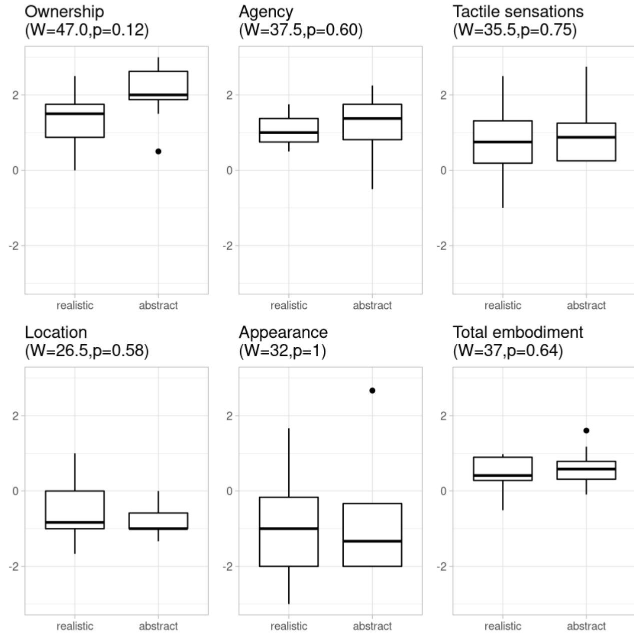

Figure 5: Boxplots with Mann–Whitney U test statistics of the questionnaire results about the presented hand (scale ranging from "I strongly disagree" = -3 to "I strongly agree" = 3).

weight discrimination. There was no measurable effect of virtual limb appearance on weight discrimination which is believed to be a direct indicator of limb ownership [3]. In our case however there was no significant difference in embodiment between our hand appearances which is more similar to findings of Matsumiya [23]. Additionally weight discrimination was not affected by varying levels of visual noise, in form of contrast variation, like spatial localisation and embodiment was, as reported by Matsumiya [23]. This indicates a different way of mental processing between those stimuli. Consequently, we must assume that weight perception is not a quantitative measure for the degree of embodiment. Our observed CVs are not similar to those reported by Matsumiya [23]. The lowest level of variation occurred at a contrast of 3.5%. Interestingly one participant reported the "sweet spot" contrast level to be a middle ground of high and low contrast. Embodiment scores did not significantly differ between the two hands, even though many participants thought they had used the abstract hand when they actually had the realistic, human hand. This further supports the assumption of virtual limb appearance being not relevant for embodiment. However there was a highly significant effect on response time. Being able to control one's hands faster could be seen as an indicator of embodiment, which is contradicting the assumption of virtual limb appearance being irrelevant for embodiment.

Furthermore, we did observe a higher weight discrimination threshold than Weber's [37] 10%. With the JND of the whole sample being just above 28g at 28.61g we actually got a Weber-fraction of 15% for our experimental setup. We therefore assume there is some sort of negative effect when using virtual reality that affects haptic perception in regards to weight discrimination. One potential reason for this could be the distraction from the task by the unfamiliar virtual environment. Another conceivable cause could be that the glove pairs and the active markers attached to them stopped participants from using natural hand and arm postures.

5.1 Limitations

Our findings show that the appearance of the hand has no effect on weight perception. This might either occur due to an insufficient contrast difference between the five levels, or due to too little exposure time. We chose these contrast levels to be in exact alignment with those reported by Matsumiya [23].

Some of the participants noted hand and finger positioning errors. Errors like these either when OptiTrack loses track of markers because the view on them is obstructed, or when markers are too close to each other and no longer discernable from each other for OptiTrack. This behaviour however was expected, since some markers are hidden to some of the tracking cameras because of our tackle. The other tracking cameras can compensate this effect, but only to some degree. Similarly both tracked tennis balls began to jitter, if there was a tracking error present.

We noticed that most of the participants (13 out of 16) thought they had been using an abstract hand representation. This was most likely due to the grey colouring of the hand which was interpreted as abstract.

The possible error in weights is another limiting factor. However, a measurement error of $\epsilon = \pm$ 3g could not be avoided. This occurred due to the friction of the ball bearings and the inaccuracy of our newton meter. One reason of implementing the apparatus was to eliminate the element of human error when selecting the weights for the participants. Another was to simplify the tracking of the objects that participants interact with, as we only needed to track the two ropes for the entirety of the experiment instead of seven different weights.

The size of the apparatus limited us to using seven weights in addition to the reference weight at maximum. While using more weights would have made the completion time of all tasks much longer, it would also have provided us with additional data. Since the experiment was already considerably long using six weights plus reference weight, we chose not to use a seventh non-reference weight.

We did not tell our participants in which order the weights had to be pulled down, but found that most of them quickly defaulted to an order of right first, left second. This might have had some influence on what weight the participants chose when the weights were similar and thus harder to be differentiated from each other.

5.2 Future work

More research is needed to get a better understanding of weight perception in general and specifically inside virtual reality. The clearly higher just noticeable difference threshold indicates an influence of VR towards visual-haptic processing. To quantify this effect we propose a study that compares real and virtual environment via a 2AFC weight discrimination task.

To further inspect the effects of visual noise on tactile processes one could change our experimental setup to account for different embodiment by grouping contrast conditions. A participant needs to do each weight difference condition for one contrast level and then has to answer a questionnaire concerning embodiment. This is especially useful because limb appearance seems to be no reliable indicator for embodiment in low contrast tasks.

Furthermore, more research is required to find an objective measurement for Limb Ownership in VR, as we could show that weight perception is not able to fulfill this role. Future research could examine other purely visual 2AFC tasks, or other visual-haptic tasks.

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