MSc Thesis

The Virtual Rubber Hand Illusion: Moving in the Right Direction?

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Paper

The Virtual Rubber Hand Illusion: Moving in the Right Direction?

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***Abstract*—The Rubber Hand Illusion is an illusion in which visual cues of stimulation on a fake hand are combined with synchronous tactile cues on a participant's hand, which can induce a sense of bodily ownership of the fake hand. This technique does not facilitate synchronous movement of the hands, and asynchronous stimulation or movement can break the illusion, thereby limiting potential benefits that bodily ownership may have in practical applications such as telerobotic control. This study aims to quantify to what extent a Virtual Reality headset with hand tracking capabilities can be used to evoke a rubber hand illusion, and to what extent the illusion strength maintains during voluntary hand movement. Twelve subjects were randomly presented with three conditions; the classic Rubber Hand Illusion (RHI), serving as a baseline for comparison, the static Virtual reality Rubber Hand Illusion (VRHI), the virtual reality equivalent of the original experiment, and the moving Virtual reality Rubber Hand Illusion (mVRHI), where participants' voluntary hand movements were tracked using motion controllers, to generate simultaneous virtual hand motion. Illusion strength was quantified subjectively, by a 27-question questionnaire adapted from literature, and objectively, by measuring proprioceptive drift; the distance between perceived hand location and actual hand location. It was hypothesized that VRHI and mVRHI would increase the strength of the illusion, compared to RHI. A significant increase in proprioceptive drift was found between the RHI and VRHI conditions. Questionnaire scores in the ownership category were significantly higher for VRHI, and the control category showed higher scores for mVRHI. In conclusion, a higher embodiment was achieved during VRHI, but mVRHI did not improve upon VRHI as expected.**

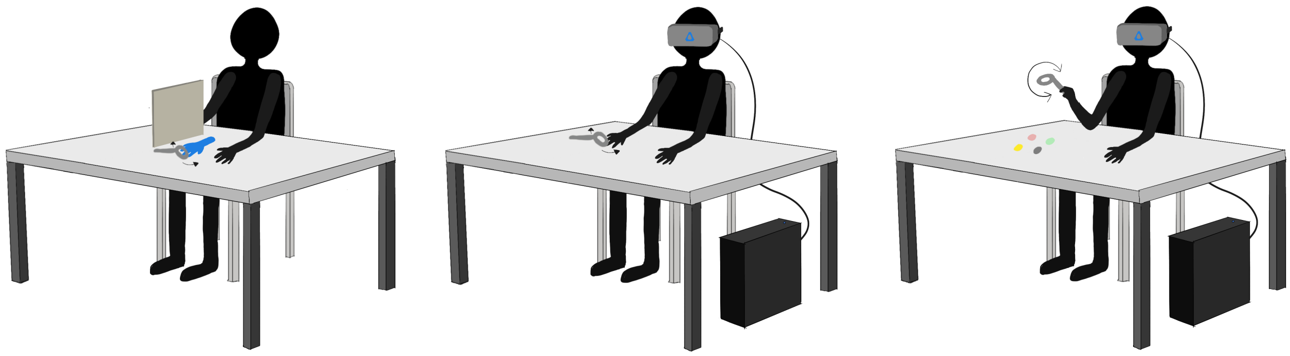
***Index Terms*—Rubber Hand Illusion, Virtual Reality, motion tracking, telepresence, embodiment, bodily ownership, proprioceptive feedback.**

I. INTRODUCTION

VIRTUAL REALITY (VR) often gives participants the sense that the virtual environment in which they find themselves is real [1]. This sense of being in the virtual environment is referred to as presence [2] or telepresence [3], where telepresence specifically refers to an environment generated by mediated means. An important aspect of telepresence is high-quality sensory feedback [4], which can make or break the illusion of being in the environment. Telepresence from virtual reality is also used in VR body illusions, for which it is seen as a prerequisite for embodiment [5]. It has been shown that virtual reality body illusions with high telepresence are strong enough to experience an entire mannequin's body as one's own [6]. This is achieved through a manipulated visual perspective combined with synchronous tactile feedback, causing the brain to fail to integrate this sensory information [7]. The sense of bodily ownership is related to activation of premotor cortex neurons, integrating visual-, tactile- and proprioceptive sensory feedback [8]. This is also the case [9] for the Rubber Hand Illusion (RHI), a multimodal perceptual body illusion, in which a subject can have the sensation that a fake hand belongs to their own body, while their real hand lies behind a vision-obscuring screen [10]. This is achieved through simultaneous tactile stimulation of the fake- and real hand with a physical object.

We have seen that body perception depends on other factors besides the visuotactile information that the RHI uses to induce the sense of bodily ownership. Proprioceptive information also provides information to the brain that may benefit the RHI when applied appropriately. However, the RHI does not make use of proprioceptive feedback, since moving one's hand will lead to incongruent visuoproprioceptive sensory information (as the fake hand does not move), which degrades the illusion [11]. Using VR with accurate hand tracking allows us to address this problem. While some studies have experimented with adding some form of movement to the RHI [12], [11], [13], it has not led to conclusive results on how individual types of sensory information influence the strength of the illusion. In short, to the best of our knowledge there is no study that used immersive VR with hand tracking capabilities for the RHI in order to try to achieve a stronger illusion. A stronger illusion would mean higher telepresence and embodiment, which could be beneficial in fields such as teleoperation, and more specifically, telerobotics [14]. The field of telerobotics has many practical applications that could benefit from a high sense of telepresence and even a sense of bodily ownership of the slave device. For instance, many forms of telerobotic surgery [15] or control of teleoperated robots conducting scientific operations on planetary bodies in outer space [16]. These applications all rely on accurate movements requiring high spatial awareness [17], which can be improved by a high sense of telepresence.

Therefore, the purpose of the current study was twofold: first, determining the effect on illusion strength (in comparison to the original experiment) when using VR instead of a rubber hand during visuotactile stimulation; and, second, whether adding proprioceptive feedback in the form of active movement -also using VR- would facilitate a more robust illusion. By using VR and motion controllers, a near-perfect synchronization (the HTC Vive system comes with a latency of $<$50 ms) between the participant's real hand and the fake hand was obtained, thereby constantly providing matching visual



(a) RHI - Baseline (b) VRHI - Virtual Reality RHI (c) mVRHI - moving Virtual Reality RHI

Fig. 1. Illustration showing the three different experimental conditions. On the left, figure 1a shows the baseline condition, replicating the original RHI experiment. In figure 1b, the participant can be seen wearing the VR headset while the right hand is being stimulated with a tracked motion controller, the controller supplies positional information to the headset, so the participant sees the virtual hand being stimulated simultaneously. The final condition, in figure 1c, shows the participant holding and moving the controller while wearing the VR headset, giving synchronous visual-proprioceptive information to the participant. The colored stickers on the table were used for touching tasks, thereby giving tactile feedback simultaneously.

and proprioceptive sensory input. In other words, movement of both fake- and real hand occurred at the same time and in the same fashion (e.g. translation, rotation and speed).

Three conditions were presented to participants in a random order: in order to provide a baseline to compare the VR and movement conditions against, an original RHI condition was arranged. This control condition was executed in the same manner as in Botvinick and Cohen's (1998) study [10]. In both other conditions, VR was used to provide the participants with visual sensory feedback; a visual-tactile condition analogous to the original RHI condition, to assess the influence of different visual sensory information provided by VR, and a visual-tactile-proprioceptive active movement condition. In this condition, participants were instructed to actively move their own hand, while following certain patterns to ensure no differences occurred between participants. See figure 1 for some simplified illustrations of the conditions.

Although 80% of participants report the RHI within the first 15 seconds of tactile stimulation [18], [19], [20], for some people it can take up to 2.5 minutes to obtain a 'compelling illusion' [21]. Therefore, in the current study a stimulation period of 3 minutes was used in all conditions. Using this protocol, every participant received the same sensory feedback, allowing for equal measurements and fair comparison between all three conditions. The impact of VR and movement on the strength of the illusion and bodily ownership was quantified using two metrics, an objective measure of proprioceptive drift, a perceptual judgment in which the indicated felt position of their unseen stimulated hand is compared with the actual position of their hand, and a subjective 27-point questionnaire adapted from [22] where participants indicated their level of agreement with the statements on a 7-point Likert scale.

For the current study we submit the following two main hypotheses; first, that the change in visual feedback (through VR) would have a positive influence on illusion strength, by providing a more realistic setting without a physical fake hand and a vision-obscuring screen. Previous studies have shown that realism is an important factor in the RHI experiment [23], [24], [25]. Second, that the added synchronous proprioceptive feedback would have a positive influence on illusion strength since this type of sensory information is integrated together with visual- and tactile information to form the bodily self-image. Adding this third form of feedback would provide a more complete image and a greater sense of ownership. Both alterations are expected to achieve both higher questionnaire responses and proprioceptive drifts than the baseline condition.

II. Methods

A. Participants

Twelve participants (mean age = 30.2 years, 4 female and 8 male, 3 left- and 9 right-handed) with normal or corrected-to-normal vision participated in this study after giving their informed consent (see Appendix A). No compensation was awarded for participation in the experiment. The experimental protocol was approved by the Delft University of Technology Ethics Committee (the Netherlands).

B. Apparatus

For this experiment the HTC Vive virtual reality system was used, consisting of a head-mounted display (HMD), two motion controllers and two base stations. The HMD has an OLED display with a resolution of 2160×1200 and a field-of-view of $110°$, displayed at 90 Hz. The base stations track the position and rotation of the HMD and the controllers in the tracking area, in which they are positioned on opposing sides, diagonally. The HTC Vive system was set up in an experiment area of approximately 4 by 2.5 meters. For the Rubber hand Illusion, an anatomically correct wooden right hand was used, covered with a rubber glove.

C. Virtual Environment

We created the virtual reality environment using Autodesk Maya and Unreal Engine 4, and developed it so that it

Fig. 2. The virtual environment for the static VRHI condition, with the participant in the actual experiment room in the bottom-right corner. The colored stickers placed on the table(s) represent reference points for the proprioceptive drift measurements and calibration purposes. The experiment leader sat on the opposing side of the table, and used a motion controller to stroke and tap the right hand of the participant, who received congruent visual feedback from the motion controller in VR.

replicated the real environment in such a way that objects that the participant came into contact with matched as close as possible with the objects in the actual experiment room. For instance, the table and chair that the participant sat at were given the exact same size and material properties. This makes sure that the participant gets no conflicting tactile- and visual sensory information. In the virtual environment, a virtual character was seated at the table following the same posture as the participant in the specific condition. In the static VRHI condition, the character was also static, sitting with both arms resting on the table in front of him. For the dynamic mVRHI condition, the joints implemented in the character's arms, wrist and fingers were used to allow the character to naturally follow the movement of the motion controller, which was tracked by the VR system. To ensure that the virtual environment was synchronized accurately to the real environment at all times, the origin $(x, y, z : 0, 0, 0)$ of the virtual environment was linked to the origin of our actual experiment area, which was checked and synchronized every time prior to a participant starting a VR condition. Since the original RHI experiment introduces an offset between the fake hand and the participant's actual hand due to the placement of the vision-obscuring screen, the location of the virtual right hand had to be given the same offset to enable equal measurements of proprioceptive drift. Therefore, in the VR conditions, the location of the virtual right hand and the controllers were given an offset of 22 centimeters (which equaled the offset in our classic RHI condition) to the left, from the participant's perspective.

D. Experiment design

Participants were asked to take a seat at the table, and were instructed to remove any jewelry and accessories from their hands and arms. Three different conditions were presented, in random order. The first condition was the classic Rubber Hand Illusion ('RHI'), for this condition participants were asked to wear a rubber glove on their right hand and place it on the table in the same posture as the fake hand. This was done in order to have as much visual congruence between the fake and real hands, as a postural [26] or visual [23] mismatch can have detrimental effects on the strength of the illusion. Then, a cardboard screen was placed between the fake and real hands, in such a way participants could not see their right hand behind the screen. A towel was also draped over the subject's right shoulder and arm so that it was not possible to see their own arm and lack of arm connected to the fake hand. Their left hand was to be placed on the table in a relaxed, natural position. Then the tactile stimulation of 3 minutes commenced, during which the subject was instructed to not move their hands and to watch the rubber hand being stimulated. This stimulation was done using the HTC Vive's controllers (for continuity, as they are also used in the VR conditions) and consisted of tapping and stroking motions, applied to both fake and real hands synchronously.

The second condition was the virtual reality equivalent of the normal RHI, the Virtual reality Rubber Hand Illusion ('VRHI'). See figure 2. For both VR conditions, participants were asked to roll up their sleeves to elbow height, for correct

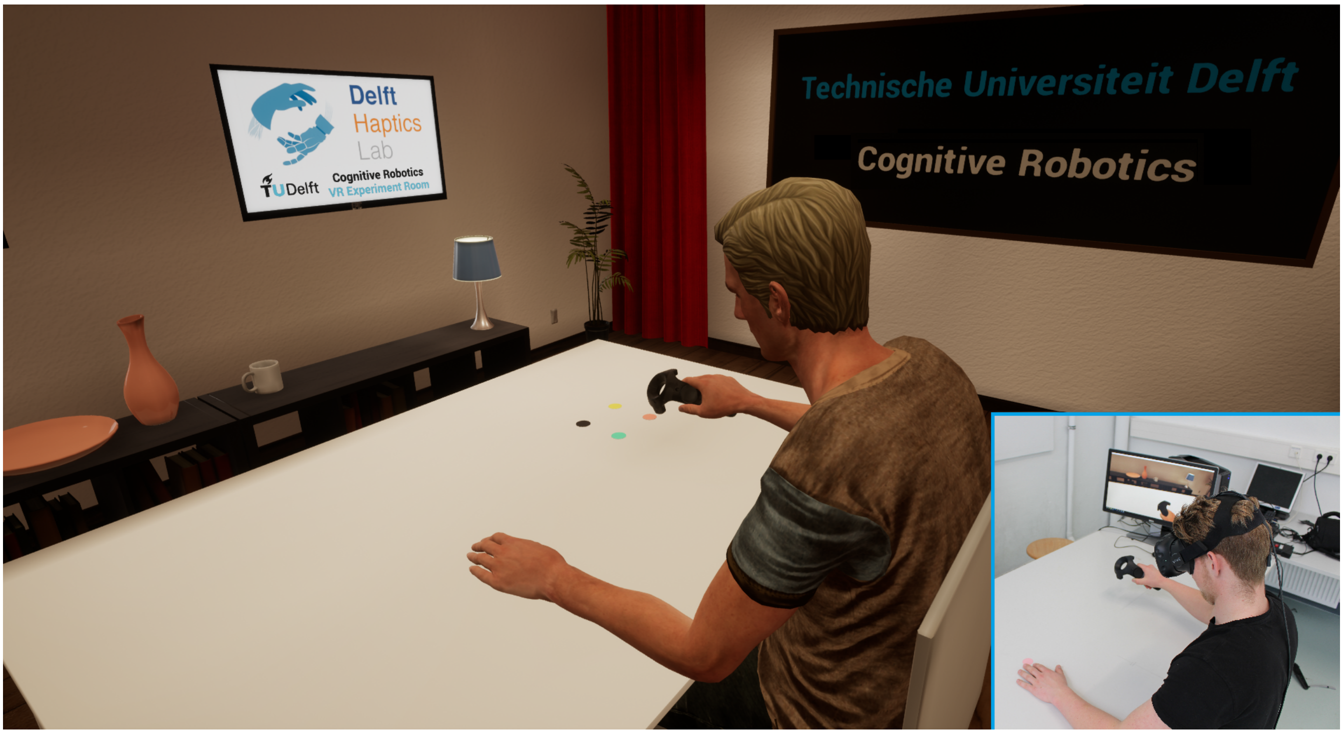


Fig. 3. The virtual environment for the dynamic mVRHI condition, with the participant in the actual experiment room in the bottom-right corner. In this condition, the participant held one of the motion controllers in the right hand, which will then be used in some simple motion- and touching tasks, instructed by the experiment leader, who sat on the opposing side of the table. The colored stickers placed on the table(s) represent reference points for the movement tasks and proprioceptive drift measurements.

tactile feedback from the table, since the virtual character was wearing short sleeves. Participants were asked to place their right hand in a pre-designed position, outlined on the table. Participants were fitted with the HMD and entered the virtual reality environment where the RHI was replicated, again for 3 minutes and using the motion controller. Participants' right hand was stroked and tapped using the controller, which was linked to the virtual space in a way that the subject received congruent visual cues with the tactile feedback from the controller.

In the third condition, the moving Virtual reality Rubber Hand Illusion ('mVRHI'), proprioceptive feedback was added. See figure 3. After taking place at the table and placing the HMD on their heads, participants were handed one of the system's motion controllers. Participants were given instructions on specific movement patterns that were to be executed, as well as some simple reaching tasks. These tasks consisted of using the controller to tap four colored stickers that were placed on the table, in a predefined order. This was done to give the subject proprioceptive- and tactile feedback in a controlled, consistent manner. After entering the VR space, participants were guided through the tasks to be completed which took around 3 minutes.

E. Measures

1) Proprioceptive Drift: After each condition, Proprioceptive Drift (PD) was measured. This was done by asking participants to close their eyes immediately after the 3-minute stimulation period and using their non-stimulated left hand index finger to point to the location of their right hand index finger. The error that occurred in this pointing task was measured, in centimeters, positive toward the left of their actual right hand position. To measure PD accurately (to about $\pm 1mm$), a standard 1-mm interval ruler was drawn on the table, originating from the pre-defined right hand position and positive towards the left of this position.

2) Questionnaire: After the PD measurement, a 27 point questionnaire adapted from [22] was answered. These questions were to be answered on a 7-point Likert scale, ranging from -3 (strongly disagree) through 0 (neither disagree nor agree) to +3 (strongly agree). The entire questionnaire can be found in appendix B. The questions that were most relevant to the effect we were trying to evaluate were categorized as *primary questions* while the other, *secondary questions* were less relevant to our study. For instance, a question (number 3) from the primary group was "...it seemed like the rubber/virtual hand belonged to me". This question directly addresses the most important effect of the study while a question (number 19) from the secondary group "...it seemed like I had three hands" has little value for the hypotheses we are evaluating.

Then, in order to make a clear comparison between the different effects of the illusion, the primary questions were divided in three categories, each representing a certain aspect of the illusion. The categories were as follows: the *ownership* category contains questions that assess the strength of the sense of ownership a participant has over the fake hand. The *tactile sense* category questions evaluate to what extent participants had the sensation that the tactile stimulation was felt where it was visually observed, on the fake hand. Finally, the *control* category determines how strong the participant's sense of control over the fake hand is. The questions in each category were as follows:

During the experiment there were times when:

Ownership (Questions 1 through 5)

1 ...it seemed like I was looking directly at my own hand, rather than at a rubber/virtual hand.
2 ...it seemed like the rubber/virtual hand began to resemble my real hand.
3 ...it seemed like the rubber/virtual hand belonged to me.
4 ...it seemed like the rubber/virtual hand was my hand.
5 ...it seemed like the rubber/virtual hand was part of my body.

Tactile sense (Questions 8 and 27)

8 ...it seemed like the touch I felt was caused by the controller touching the rubber/virtual hand.
27 ...it seemed like I was feeling the touch of the controller in the location where I saw the rubber/virtual hand being touched.

Control (Questions 9 and 10)

9 ...it seemed like I could have moved the rubber/virtual hand if I had wanted.
10 ...it seemed like I was in control of the rubber/virtual hand.

III. Results

The two main hypotheses mentioned in the previous section regarding the role of VR and proprioceptive stimulation in illusion robustness were statistically tested. The results of the current experiment will be presented in two sections. The questionnaire and proprioceptive drift results will be presented separately in the first and second section, respectively.

During the experiment and later during data analysis, it became clear that one participant was totally unaffected by the RHI in all its iterations. Due to the severity of the outliers in this participant's results, these results skewed the data significantly. Therefore, this participant was removed from the data set and was replaced with a new, random participant to complete the latin square design of the experiment. No sex-, age- or handedness-related differences in RHI scores were found in a preliminary analysis.

A. Proprioceptive Drift

All proprioceptive drift measurement results can be found in figure 4. In order to evaluate both our main hypotheses, between-subjects one way ANOVAs with VR/movement condition as the independent factor and proprioceptive drift score as the dependent variable were conducted between each of the conditions. This analysis yielded a significant increase in RHI effect ($F_{2,23} = 5.06, p = 0.035$) when comparing the visual-tactile VRHI condition to the baseline RHI condition and a near-significant effect ($F_{2,23} = 5.06, p = 0.065$) when comparing the visual-proprioceptive mVRHI condition to the baseline RHI condition. A comparison between the visual-tactile VRHI and visual-proprioceptive mVRHI conditions yielded no significant difference ($F_{2,23} = 0.11, p = 0.743$).

Descriptive statistics were calculated for each condition and were as follows; for the baseline RHI condition ($M = 7.54, SD = 4.25$), the visual-tactile VRHI condition ($M = 11.25, SD = 3.81$) and for the visual-proprioceptive mVRHI condition ($M = 10.73, SD = 3.80$).

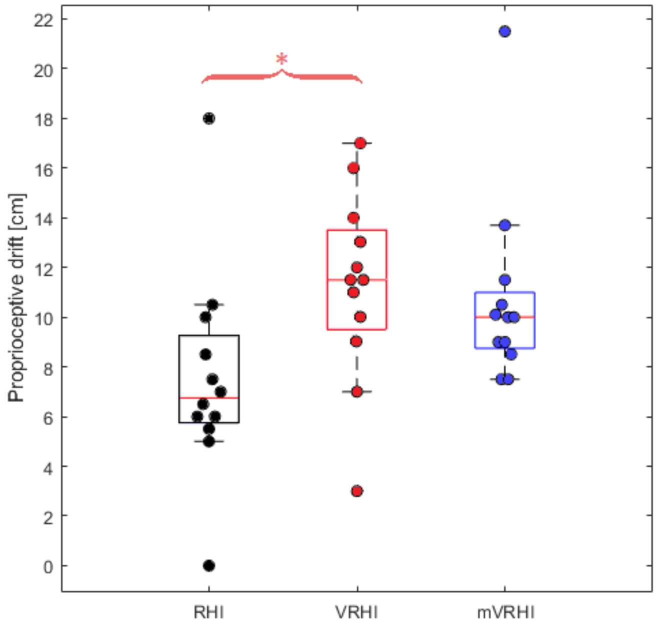


Fig. 4. Proprioceptive drift results across all participants and all conditions. Red lines indicate the median for each condition, circles represent individual measurements per condition, showing 12 measurements per experiment condition. Red accolades with a star symbol indicate that there is a significant difference between the two scores.

B. Questionnaire

Questionnaire scores for all questions across all participants, as well as a separate comparison between the primary and secondary questions can be found in figure 5. A detailed view of the primary questions, divided in the categories explained in the methods section can be found in figure 6. For a complete view of all questions' individual results, see Appendix C. To assess any global differences between the conditions in the self-report questionnaire, a Kruskal-Wallis test was conducted over all three conditions for all questions. This analysis showed that there was a significant difference between the three conditions ($H_2 = 6.9, p = 0.032$). A more specific Mann-Whitney test showed that a significant increase was found between the RHI and VRHI conditions ($p = 0.001$).

When comparing the results for the primary questions with Mann-Whitney tests, significant differences between; RHI and VRHI ($p = 0.0002$) and RHI and mVRHI ($p = 0.036$) were

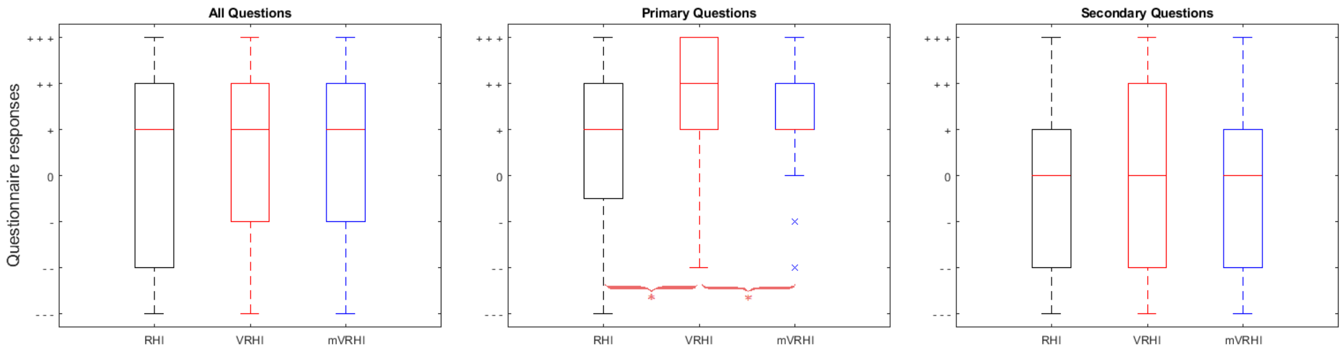


Fig. 5. Questionnaire scores for all participants for all three conditions. Black: RHI, red: VRHI, blue: mVRHI. Red lines indicate the median for each question. From left to right: all questions with 324 data points per box, primary questions with 108 data points per box and secondary questions with 216 data points per box. Red accolades with a star symbol indicate that there is a significant difference between the two scores. Error bars are 1.5 *IQR*.

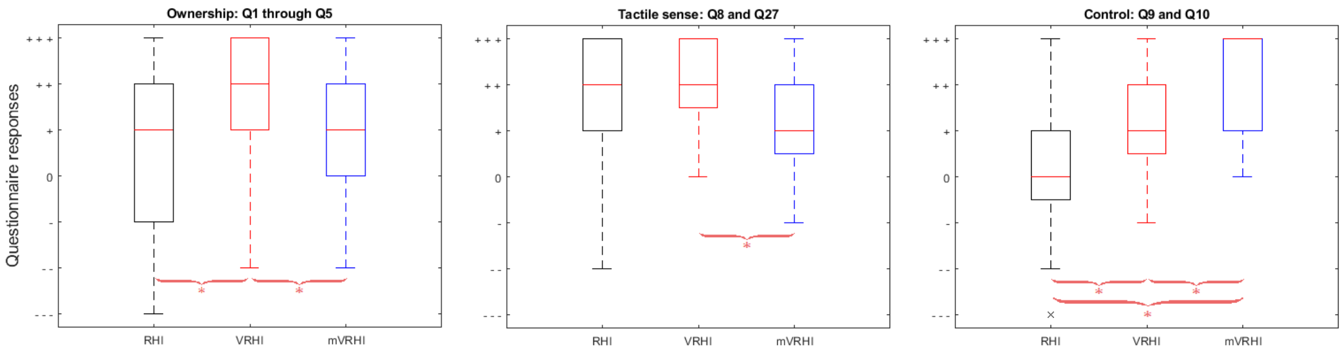


Fig. 6. Questionnaire scores for all participants for all three conditions. Black: RHI, red: VRHI, blue: mVRHI. Red lines indicate the median for each question. Categories from left to right: ownership with 60 data points per box, tactile sense with 24 data points per box and control with 24 data points per box. Red accolades with a star symbol indicate that there is a significant difference between the two scores. Error bars are 1.5 *IQR*.

found. For the secondary questions, no significant differences were found between conditions ($H_2 = 1.3, p = 0.529$).

After this global analysis, the primary question categories were each statistically tested for significant differences. This was done using Mann-Whitney tests and yielded the following results:

Ownership

- VRHI $>$ RHI ($p = 0.001$)
- VRHI $>$ mVRHI ($p = 0.004$)

Tactile sense

- VRHI $>$ mVRHI ($p = 0.022$)

Control

- VRHI $>$ RHI ($p = 0.024$)
- mVRHI $>$ RHI ($p < .0001$)
- mVRHI $>$ VRHI ($p = 0.009$)

IV. Discussion

The primary goal of this study was to analyze the effect of immersive VR visual feedback as well as adding active proprioceptive feedback on the strength of the rubber hand illusion. The hypotheses for the study were that both the change in visual feedback and the introduction of active movement would increase the strength of the illusion. Identification of the specific illusion induction strategy that provides the highest level of embodiment will facilitate development of practical applications which benefit from embodiment, such as in the field of telerobotics.

In order to assess the effect of these alternate approaches, three different human-subject experimental conditions were designed to test participants' response to VR visual feedback and active movement during the rubber hand illusion. From the data that was gathered during the experiment, we concluded that visual feedback through VR has a significantly positive effect on the strength of the illusion. Contrary to our expectations, no significant increase in strength following from the addition of synchronous active movement during stimulation was observed. A possible explanation for this unexpected result can perhaps be found in the dual effect that movement of one's hand (or any body part for that matter) has on the sense of body ownership. Although the bodily self-image is a result of the brain's processes which integrate multiple sensory cues (visual, tactile and propriocepsis) into the perception of one's own body [25], another study has shown that movement, which leads to a proprioceptive update, while not completely erasing the RHI as previously assumed, has a detrimental effect on it [11]. Therefore, if movement of a participants' actual hand occurs while the fake hand does not follow the same trajectory synchronously with it, the proprioceptive update will cause the participant to become more aware of their actual hand location. In this case, proprioception can dominate the visual sensory information when it appears to be more reliable [27]. We assumed that [11] found these results because they did not synchronize visual and proprioceptive information, movement was executed after tactile stimulation and was not linked to the fake hand. Similarly, [12] was influenced by the lack of available high-tech solutions to create a proper synchronization between visual and proprioceptive information, which was done by suspending the participants' arm from a sling and connecting it to the fake hand with a wooden rod. Perhaps the synchronization in the current study was not accurate enough as well, despite our use of one of the best virtual reality with hand tracking systems available (HTC Vive). Finally, the offset we had to introduce to the VR conditions may have had influence on the strength of the influence, since some participants indicated that they noticed the positional error when in the VR environment. They experienced a "something is not quite right" feeling, which might have had a negative effect on their level of immersion.

Our conclusion of the improvement that virtual reality has on the RHI strength in the visual-tactile condition concurs with previous studies that have shown the potential of virtual reality in similar experiments [9], [28], [5], [29], although most of these studies did not conclude the significant increase that was found in the current study. It is very likely that this contradiction arises from the difference in technical capabilities between these time periods. Similarly, in [30], virtual reality was used to perform an experiment where participants were asked to perform certain tasks involving motion, but the experimenters indicated that; 1) although results were promising, their experiment "by no means proves that the IVR arm ownership illusion is the same as the rubber hand illusion" and 2) suggested that their system of motion tracking could be improved upon. The current study has shown that a VR ownership illusion can be in fact even stronger than the (original) rubber hand illusion when executed with high precision motion tracking. The current study shows that, the slight delay in the transfer of information mattered less for tactile information than for proprioceptive information, since the synchronization of tactile information was also dependent on the tracking accuracy (and delays) of the system's motion controllers. This concurs with general consensus about the relative weighing of different sensory information types, with proprioception being the most dominant form of sensory information.

Since this study has shown that the telepresence of virtual reality is in fact strong enough to create a stronger and more convincing illusion, it would be interesting to see if in future work the addition of movement can be done in such a way that it does improve the strength of the illusion even further, which we believe to be possible. That is, if future technological developments allow for even lower delays in the tracking of motion. If these methods can then be applied in the field of telerobotics while maintaining the same low-latency transfer of information, the results could be phenomenal.

V. CONCLUSIONS

A rubber hand illusion (RHI) experiment was conducted in three different conditions to investigate the effect of visual feedback through virtual reality (VR) and active proprioceptive feedback (movement) during stimulation on the strength of the illusion. It was hypothesized that; using VR instead of an actual fake hand would increase embodiment and therefore illusion strength and, that when introducing active movement synchronized with the VR environment through hand tracking controllers the illusion strength would increase further.

For the experimental condition studied, we conclude that:

- the use of VR for visual feedback increases the strength of the RHI through higher embodiment and in terms of sense of -ownership and -control over the hand when compared to the baseline condition.
- against expectations, illusion strength did not increase by introducing synchronous active movement.
- active movement *did* give a higher sense of control over the fake hand when compared to both other conditions, according to questionnaire responses.

It can thus be concluded that VR is beneficial for inducing and maintaining a strong illusion, and that movement can increase certain aspects of the illusion, although it did not increase overall illusion strength. Altogether, during this study the visual-tactile VR condition performed best overall in both subjective- and objective measures, while also being the most well-liked condition, indicated by participants' verbal responses.

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Appendices

A

Informed Consent Form

Informed Consent Form – Virtual Reality Rubber Hand Illusion

Dear participant,

You have been asked to participate in a study on the Rubber Hand illusion combined with Virtual Reality, conducted by Casper van Lit and supervised by David Abbink. In this study the effect of Virtual Reality and movement on the strength of the Rubber Hand Illusion experiment is studied. More specifically, this study investigates the extent to which the strength of the illusion will improve when using a Virtual Reality system instead of the 'classic' Rubber Hand. Furthermore, it studies whether movement during the experiment will increase the strength of the illusion.

You will be requested to perform three different tasks in a random order with two of the tasks incorporating a Virtual Reality system. Please place the Virtual Headset on your head when instructed, and during a block please keep the headset on until instructed otherwise. You are asked to not move your hands/arms unless instructed otherwise. The tasks to be performed are as follows:

<u>Block 1 - RHI</u>

i) Take place in the participant's seat and place your arms relaxed in front of you on the table, the experiment leader will instruct you on where to place them.
ii) The experiment leader places a few necessary items on the table and explains their use. You will be asked to wear a rubber glove during this block of the experiment.
iii) After a short explanation the experiment block will start and will take around 3 minutes. During this time your hand will be stroked and tapped using a plastic object.

<u>Block 2 - VR RHI</u>

i) Take place in the participant's seat and place your arms relaxed in front of you on the table, the experiment leader will instruct you on where to place them.
ii) When instructed, place the Virtual Reality headset on your head, the experiment leader will then instruct you on where to place your hands.
iii) After a short explanation the experiment block will start and will take around 3 minutes. During this time your hand will be stroked and tapped using a plastic object.

<u>Block 3 - VR RHI/Movement</u>

i) Take place in the participant's seat and place your arms relaxed in front of you on the table, the experiment leader will instruct you on where to place them.
ii) During this experiment block, you will be holding two motion controllers, which track the movement of your hands. You will be instructed on how to hold them.
iii) When instructed, place the Virtual Reality headset on your head, the experiment leader will then instruct you on where to place your hands.
iv) After a short explanation the experiment block will start and will take around 3 minutes. During this time you can move your hands and will be instructed on how to do so.

After each block you will be asked to complete a simple pointing task which will measure performance. There will be a break between each of the three blocks where a questionnaire will be filled out. From introduction to debriefing, the experiment lasts about 30 to 45 minutes.

Participation in this study is voluntary. If you feel any form discomfort during the experiment, please inform the experimental leader. You are free to quit the experiment at any time. For questions after the study, please contact Casper van Lit (C.J.vanLit@student.tudelft.nl).

I, the undersigned, declare to have read and understood the information about the project, the use of data and to consent in the experiment.

Name: _______________

Location: _______________

Date: _______________

Signature: _______________

Basic Information

(please fill in the following questions)

What is your age? ____

What is your gender? Male/Female

Are you left- or right handed? Left/Right

How much experience with Virtual Reality have you had in the past?

Proprioceptive Drift Measure

(to be filled in by experiment leader)

Block 1: [cm]

Block 2: [cm]

Block 3: [cm]

B

Questionnaire: Form

Virtual Rubber Hand Illusion – Questionnaire Block 1

You have just completed (part of) the Virtual Rubber Hand Illusion experiment. Please fill out the following questionnaire as objectively and honestly as possible. Please answer the questions in the following range: --- (strongly disagree) through 0 (neutral) to +++ (strongly agree). There are a total of 27 questions.

During the experiment block there were times when…

#1 ...it seemed like I was looking directly at my own hand, rather than at a rubber/virtual hand.

Strongly Disagree --- -- - 0 + ++ +++ *Strongly Agree*

#2 ...it seemed like the rubber/virtual hand began to resemble my real hand.

--- -- - 0 + ++ +++

#3 ...it seemed like the rubber/virtual hand belonged to me.

--- -- - 0 + ++ +++

#4 ...it seemed like the rubber/virtual hand was my hand.

--- -- - 0 + ++ +++

#5 ...it seemed like the rubber/virtual hand was part of my body.

--- -- - 0 + ++ +++

#6 ...it seemed like my hand was in the location where the rubber/virtual hand was.

--- -- - 0 + ++ +++

#7 ...it seemed like the rubber/virtual hand was in the location where my hand was.

--- -- - 0 + ++ +++

#8 ...it seemed like the touch I felt was caused by the controller touching the rubber/virtual hand.

--- -- - 0 + ++ +++

#9 ...it seemed like I could have moved the rubber/virtual hand if I had wanted.

--- -- - 0 + ++ +++

#10 ...it seemed like I was in control of the rubber/virtual hand.

--- -- - 0 + ++ +++

#11 ...it seemed like my own hand became rubbery.

--- -- - 0 + ++ +++

#12 ...it seemed like I was unable to move my hand.

--- -- - 0 + ++ +++

#13 ...it seemed like I could have moved my hand if I had wanted.

--- -- - 0 + ++ +++

#14 ...it seemed like I couldn't really tell where my hand was.

--- -- - 0 + ++ +++

Virtual Rubber Hand Illusion – Questionnaire Block 1

During the experiment block there were times when…

#15 ...it seemed like my hand had disappeared.

Strongly Disagree --- -- - 0 + ++ +++ *Strongly Agree*

#16 ...it seemed like my hand was out of my control.

--- -- - 0 + ++ +++

#17 ...it seemed like my hand was moving towards the rubber/virtual hand.

--- -- - 0 + ++ +++

#18 ...it seemed like the rubber/virtual hand was moving towards my hand

--- -- - 0 + ++ +++

#19 ...it seemed like I had three hands.

--- -- - 0 + ++ +++

#20 ...I found that experience enjoyable.

--- -- - 0 + ++ +++

#21 ...I found that experience interesting.

--- -- - 0 + ++ +++

#22 ...the touch of the controller on my finger was pleasant.

--- -- - 0 + ++ +++

#23 ...I had the sensation of pins and needles in my hand.

--- -- - 0 + ++ +++

#24 ...I had the sensation that my hand was numb.

--- -- - 0 + ++ +++

#25 ...it seemed like the experience of my hands was less vivid than normal.

--- -- - 0 + ++ +++

#26 ...I found myself liking the rubber/virtual hand.

--- -- - 0 + ++ +++

#27 ...it seemed like I was feeling the touch of the controller in the location where I saw the rubber/virtual hand being touched.

--- -- - 0 + ++ +++

Virtual Rubber Hand Illusion – Questionnaire Block 2

You have just completed (part of) the Virtual Rubber Hand Illusion experiment. Please fill out the following questionnaire as objectively and honestly as possible. Please answer the questions in the following range: --- (strongly disagree) through 0 (neutral) to +++ (strongly agree). There are a total of 27 questions.

During the experiment block there were times when…

#1 ...it seemed like I was looking directly at my own hand, rather than at a rubber/virtual hand.

Strongly Disagree --- -- - 0 + ++ +++ *Strongly Agree*

#2 ...it seemed like the rubber/virtual hand began to resemble my real hand.

--- -- - 0 + ++ +++

#3 ...it seemed like the rubber/virtual hand belonged to me.

--- -- - 0 + ++ +++

#4 ...it seemed like the rubber/virtual hand was my hand.

--- -- - 0 + ++ +++

#5 ...it seemed like the rubber/virtual hand was part of my body.

--- -- - 0 + ++ +++

#6 ...it seemed like my hand was in the location where the rubber/virtual hand was.

--- -- - 0 + ++ +++

#7 ...it seemed like the rubber/virtual hand was in the location where my hand was.

--- -- - 0 + ++ +++

#8 ...it seemed like the touch I felt was caused by the controller touching the rubber/virtual hand.

--- -- - 0 + ++ +++

#9 ...it seemed like I could have moved the rubber/virtual hand if I had wanted.

--- -- - 0 + ++ +++

#10 ...it seemed like I was in control of the rubber/virtual hand.

--- -- - 0 + ++ +++

#11 ...it seemed like my own hand became rubbery.

--- -- - 0 + ++ +++

#12 ...it seemed like I was unable to move my hand.

--- -- - 0 + ++ +++

#13 ...it seemed like I could have moved my hand if I had wanted.

--- -- - 0 + ++ +++

#14 ...it seemed like I couldn’t really tell where my hand was.

--- -- - 0 + ++ +++

Virtual Rubber Hand Illusion – Questionnaire Block 2

During the experiment block there were times when…

#15 ...it seemed like my hand had disappeared.

Strongly Disagree --- -- - 0 + ++ +++ *Strongly Agree*

#16 ...it seemed like my hand was out of my control.

--- -- - 0 + ++ +++

#17 ...it seemed like my hand was moving towards the rubber/virtual hand.

--- -- - 0 + ++ +++

#18 ...it seemed like the rubber/virtual hand was moving towards my hand

--- -- - 0 + ++ +++

#19 ...it seemed like I had three hands.

--- -- - 0 + ++ +++

#20 ...I found that experience enjoyable.

--- -- - 0 + ++ +++

#21 ...I found that experience interesting.

--- -- - 0 + ++ +++

#22 ...the touch of the controller on my finger was pleasant.

--- -- - 0 + ++ +++

#23 ...I had the sensation of pins and needles in my hand.

--- -- - 0 + ++ +++

#24 ...I had the sensation that my hand was numb.

--- -- - 0 + ++ +++

#25 ...it seemed like the experience of my hands was less vivid than normal.

--- -- - 0 + ++ +++

#26 ...I found myself liking the rubber/virtual hand.

--- -- - 0 + ++ +++

#27 ...it seemed like I was feeling the touch of the controller in the location where I saw the rubber/virtual hand being touched.

--- -- - 0 + ++ +++

Virtual Rubber Hand Illusion – Questionnaire Block 3

You have just completed (part of) the Virtual Rubber Hand Illusion experiment. Please fill out the following questionnaire as objectively and honestly as possible. Please answer the questions in the following range: --- (strongly disagree) through 0 (neutral) to +++ (strongly agree). There are a total of 27 questions.

During the experiment block there were times when…

#1 ...it seemed like I was looking directly at my own hand, rather than at a rubber/virtual hand.

Strongly Disagree --- -- - 0 + ++ +++ *Strongly Agree*

#2 ...it seemed like the rubber/virtual hand began to resemble my real hand.

--- -- - 0 + ++ +++

#3 ...it seemed like the rubber/virtual hand belonged to me.

--- -- - 0 + ++ +++

#4 ...it seemed like the rubber/virtual hand was my hand.

--- -- - 0 + ++ +++

#5 ...it seemed like the rubber/virtual hand was part of my body.

--- -- - 0 + ++ +++

#6 ...it seemed like my hand was in the location where the rubber/virtual hand was.

--- -- - 0 + ++ +++

#7 ...it seemed like the rubber/virtual hand was in the location where my hand was.

--- -- - 0 + ++ +++

#8 ...it seemed like the touch I felt was caused by the controller touching the rubber/virtual hand.

--- -- - 0 + ++ +++

#9 ...it seemed like I could have moved the rubber/virtual hand if I had wanted.

--- -- - 0 + ++ +++

#10 ...it seemed like I was in control of the rubber/virtual hand.

--- -- - 0 + ++ +++

#11 ...it seemed like my own hand became rubbery.

--- -- - 0 + ++ +++

#12 ...it seemed like I was unable to move my hand.

--- -- - 0 + ++ +++

#13 ...it seemed like I could have moved my hand if I had wanted.

--- -- - 0 + ++ +++

#14 ...it seemed like I couldn't really tell where my hand was.

--- -- - 0 + ++ +++

Virtual Rubber Hand Illusion – Questionnaire Block 3

During the experiment block there were times when…

#15 ...it seemed like my hand had disappeared.

Strongly Disagree --- -- - 0 + ++ +++ *Strongly Agree*

#16 ...it seemed like my hand was out of my control.

--- -- - 0 + ++ +++

#17 ...it seemed like my hand was moving towards the rubber/virtual hand.

--- -- - 0 + ++ +++

#18 ...it seemed like the rubber/virtual hand was moving towards my hand

--- -- - 0 + ++ +++

#19 ...it seemed like I had three hands.

--- -- - 0 + ++ +++

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#21 ...I found that experience interesting.

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#22 ...the touch of the controller on my finger was pleasant.

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#23 ...I had the sensation of pins and needles in my hand.

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#24 ...I had the sensation that my hand was numb.

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#25 ...it seemed like the experience of my hands was less vivid than normal.

--- -- - 0 + ++ +++

#26 ...I found myself liking the rubber/virtual hand.

--- -- - 0 + ++ +++

#27 ...it seemed like I was feeling the touch of the controller in the location where I saw the rubber/virtual hand being touched.

--- -- - 0 + ++ +++

C

Questionnaire: Complete Results

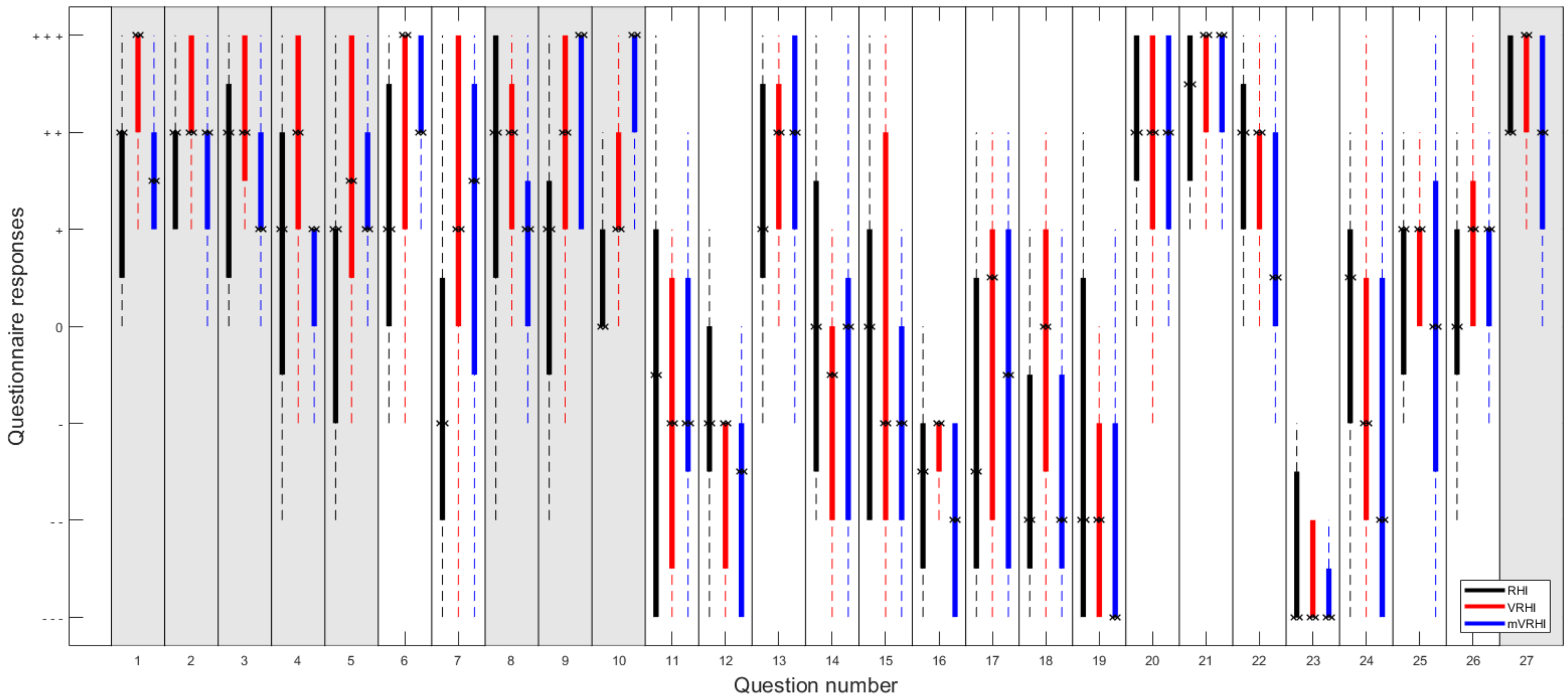

Figure C.1: Questionnaire scores for all participants for all three conditions. Black: RHI, red: VRHI, blue: mVRHI. Questions belonging to one of the three selected question categories are highlighted grey. Black crosses indicate the median for each question. Each bar shows 12 data points corresponding to the question answers of each participant. Error bars are one *IQR*. Outliers are not displayed in this figure to prevent visual cluttering.

D

Equipment, Setup and Configuration

Setup & Configuration

Hardware setup

The experiment was conducted using an HTC Vive. This VR headset was chosen because of its high resolution and low latency, to make the experiment feel as realistic and smooth as possible. In order to run the experiment, hardware of sufficient power was needed. After research into the specific requirements, a desktop PC was acquired that powered the VR environment during the experiment. This was the Alienware Aurora R5, with the following specifications:

- CPU: 4GHz Intel Core i7-6700K (quad-core, 8MB cache, up to 4.2GHz with Turbo Boost)
- Graphics: Nvidia GeForce GTX 1080 (8GB GDDR5X RAM)
- RAM: 16GB DDR4 RAM (2,133MHz)
- Storage: 256GB PCIe SSD, 2TB HDD (7,200RPM)
- Optical drive: Tray-loading dual layer Blu-ray reader
- Ports: 7 x USB 3.0, 1 x USB 3.1 Type-A, 1 x USB-3.1 Type-C, 6 x USB 2.0, Ethernet, 4 x DisplayPort, HDMI, optical out, headphone jack, microphone jack, 7.1 surround sound out.

As mentioned, the VR headset that was used was the HTC Vive, which has the following (most important) specifications:

- Display: OLED
- Resolution: 2160x1200
- Refresh rate: 90Hz
- Platform: SteamVR, VivePort
- FOV: 110 degrees
- Tracking area: 5x5 meters
- Sensors: Accelerometer, gyroscope, lighthouse laser tracking system, front-facing camera
- Connections: HDMI, USB 2.0, USB 3.0

Software setup

After arranging the hardware, Steam's SteamVR (https://www.steampowered.com) was acquired to run the HTC Vive, this is the standard software that is required by the HTC Vive to run. After configuration of the setup and the experiment area, the system was ready to use. To build the virtual reality experiment room, two software packages were used: *Autodesk Maya* and *Unreal Engine 4*, both of which will now be shortly explained.

Autodesk Maya

(Autodesk) Maya (https://www.autodesk.com/products/maya/overview) is a computer program that is used for creating and animating complex 3D-models. These models are often used in the movie and television industries, and also in computer games. It is one of the most popular programs in this field, mostly due to the large range of possibilities and openness for developers. For the current study, Maya was used for 3D-Modeling only, animations and other functionality were developed in Unreal Engine 4. Maya was used because of the good compatibility it has with Unreal Engine 4.

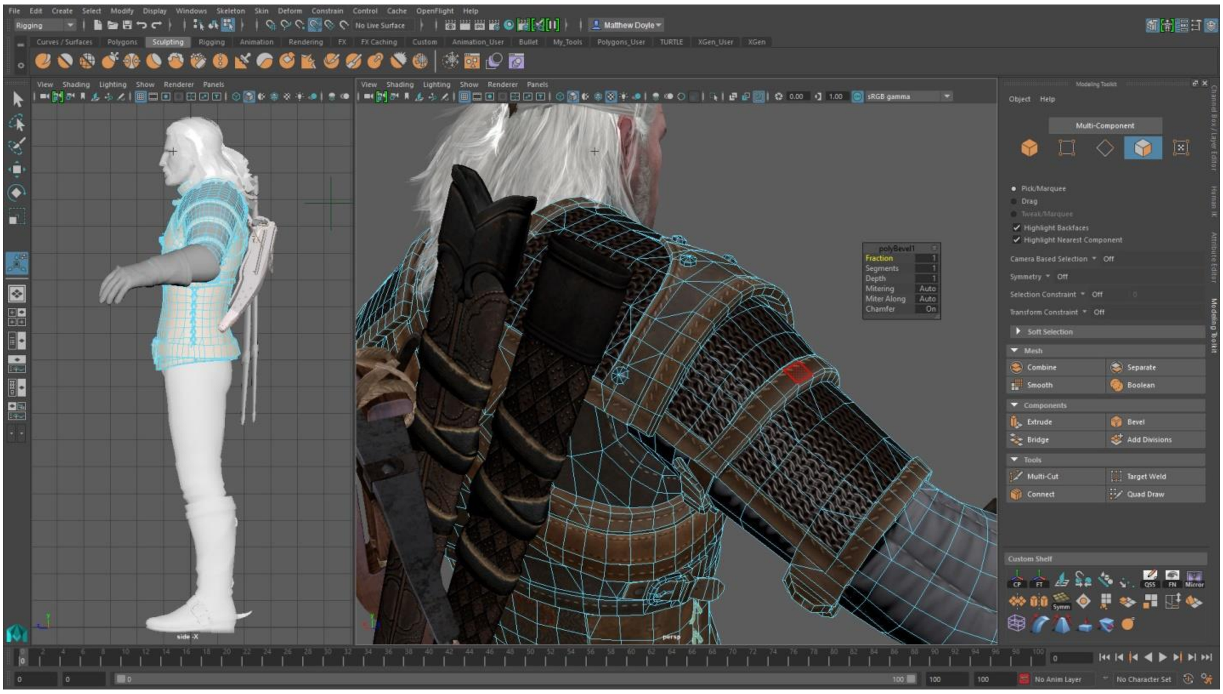

Figure 1: Example of model-creation in Autodesk Maya[1]. From (https://www.autodesk.com/campaigns/autodesk-for-games)

In figure 1 an example of a model which is being built in Maya can be seen. The light blue lines separate the polygons of which a model is constructed. The edges of the screen show the interface of Maya.

Unreal Engine 4

Unreal Engine (https://www.unrealengine.com) is a widely-used game engine, developed by the game studio Epic Games (https://www.epicgames.com). Initially mostly used for first-person games, later also for third-person games. In the current study, the newest iteration of the engine, Unreal Engine 4 (UE4) was used. This engine was chosen since it works seamlessly with virtual reality (built-in functionality), the degree of realism that can be achieved with environments developed using this engine, and the technical possibilities in terms of functionality which the engine offers. The functionality a certain object has is defined using “Blueprints”, the advanced drag-and-drop system of the engine, based on the C++ programming language.

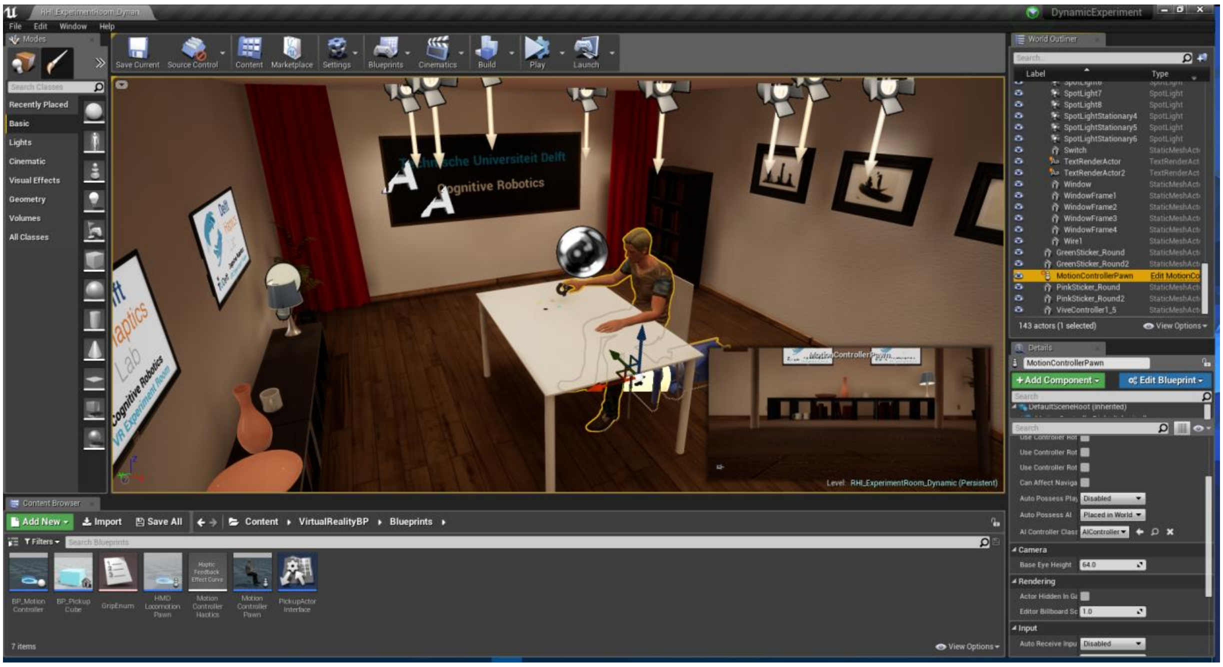

Figure 2: Development of the virtual reality environment in Unreal Engine 4.

In figure 2 the interface of UE4 during creation of the virtual environment can be seen. In the middle of the screen (the viewport) we see the environment visually represented, with all visible and non-visible (such as reflection capture spheres: the silver circle in the middle) items. Non-visible items may interact with the environment in a way that is not directly visible when in the environment. For instance, the reflection capture sphere influences how and what a reflective surface encapsulated by it reflects to the user in the environment.

Example work-flow

1) Create polygonal 3D-model in Maya
2) Export model to UE4
3) Place model in environment
4) Texture the model as realistic as possible
5) Create functionality of object (when needed). See figure 3.

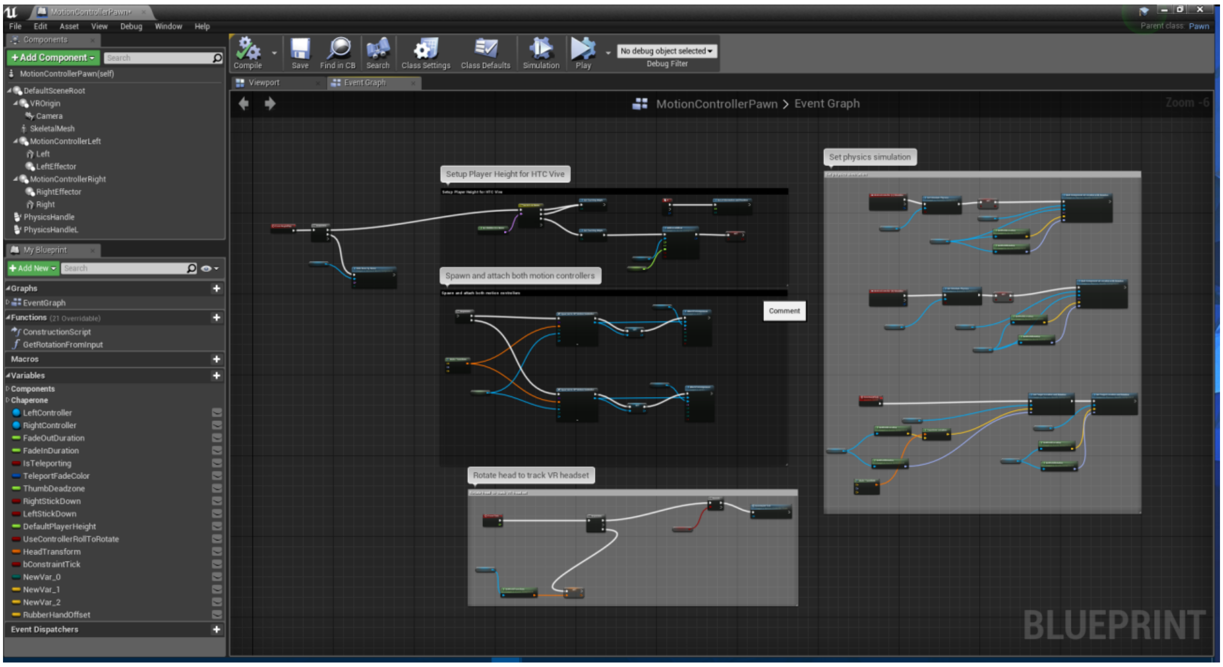

Figure 3: Blueprint of the "pawn" in the virtual reality environment.

Figure 3 shows an example of a blueprint in UE4. In this case, this blueprint represents (part of) the functionality that lies within the "pawn", which is a class of actors in the environment that can be controlled by a player or AI. In this case, our pawn is the character sitting at the table. When in the environment through VR, the user sees through the eyes of the pawn.

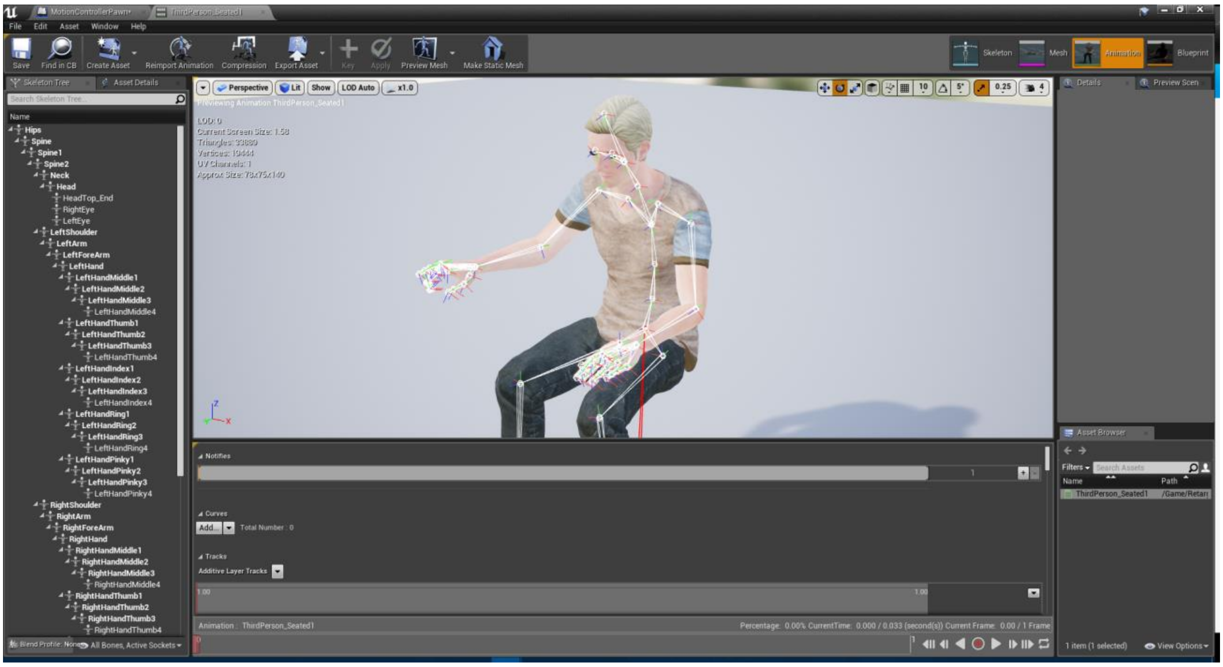

Figure 4: The character used in the virtual reality environment. The white lines represent the bones in the body.

The most challenging part of this development process was the implementation of the motion tracking delivered by the HTC Vive. Since our experiment required very high accuracy, due to the analogous way that proprioceptive drift was measured, the motion tracking had to be very precise, and reproducible.

This was achieved through very precise configuration of the environment, and the implementation of a reliable calibration function, which was executed prior to every use of the environment.

Experimental Design

During the development of the experiment and the virtual reality environment for it, a few important aspects had to be carefully considered and changed when necessary.

<u>VRHI</u>

Figure 5: Left hand being stimulated in the VRHI condition.

At first, the idea was to stimulate both hands with a controller separately at the same time, so that there would be more impulses for embodiment. The problem with this strategy was that, although possibly higher telepresence could be achieved, when the left hand was also stimulated, it could no longer be used to point toward the right hand (since this would break the embodiment of the fake left hand anyway), to measure proprioceptive drift. Therefore it was decided that only the right hand would be stimulated.

Figure 6: Right hand being stimulated with two controllers simultaneously.

After it was decided to use only the right hand for stimulation, we had an extra controller “to spare” since it would only require one controller to stimulate both real- and virtual right hand at the same time. For a short time we considered using two controllers to stimulate the right hand, for more impulses, perhaps leading to higher embodiment. During testing, we concluded that: 1) using two controllers was not very practical due to their size and how they would move over the hand, and 2) it was not possible to do this for the baseline RHI condition, meaning that equal comparison between the results would not be possible.

mVRHI

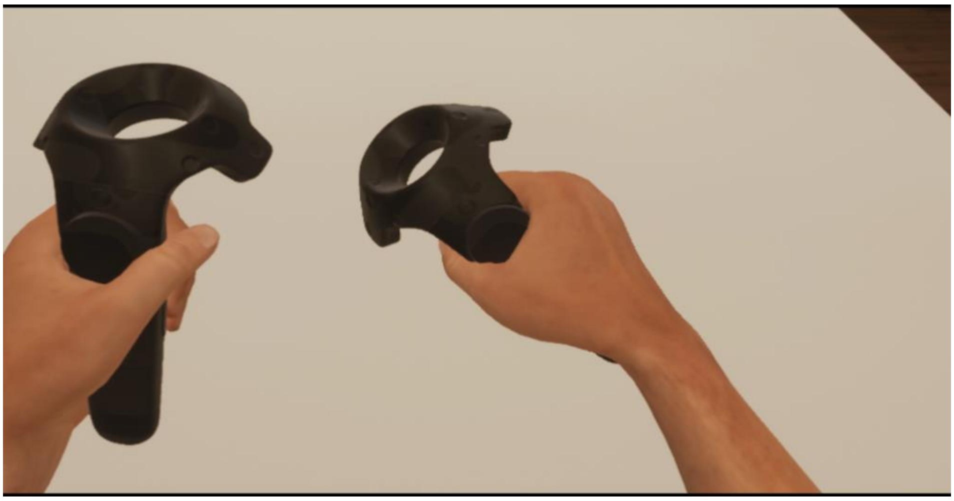

Figure 7: Participant holding and voluntarily moving two motion controllers simultaneously.

For the movement condition, there were a few considerations. First, whether or not the participant should use both motion controllers to move both hand simultaneously. The idea was again that this would result in more impulses and thus higher telepresence. Again, we concluded that this would eliminate the possibility to 1) measure proprioceptive drift and 2) make an equal comparison between this condition and the other two conditions. The same conclusions were drawn for the following idea, the principle of self-touch:

Figure 8: Participant touching their own left arm during stimulation.

Although this would add very realistic tactile feedback, it came with the same limitations as using two controllers for the mVRHI condition.

Other considerations

Two other aspects of the experiment were discussed at some point. First, the offset that was created in both VR conditions to match the innate offset of the baseline RHI condition. To match this offset, we had to purposefully interfere with the accuracy of the motion controllers, to give them the same 22 cm offset. Although this enabled us to measure proprioceptive drift in the VR conditions, it is possible that this may have made the illusion less realistic for participants as the location of their fake hand did not match that of their real hand. Using VR it would have been possible to create the fake hand in the exact same location as the real hand and perhaps create an even more convincing illusion. This would leave just the subjective questionnaire as measurement, and we decided that the objective proprioceptive drift measurement was more important to keep for comparison reasons.

Second, the movement patterns that were executed by participants during the mVRHI condition. We had the choice of giving people the freedom to do whatever they wanted with their right hand, since the motion controller would track this movement perfectly and give matching visual information through the headset. Although this would eliminate the need for specific instructed movements and perhaps create a more realistic environment, due to the randomness of what kind of movements different participants would execute, we decided that this would interfere with our ability to make equal comparisons between participants in the mVRHI condition, and opted to allow participants to only make specific, instructed movements.

Pilot experiment

When the experiment was properly laid out, we conducted a pilot experiment with two participants. Although we had some technical difficulties during the pilot experiment preventing us from gathering useful data, the pilot was successful and the participants were very enthusiastic about the experiment. After some minor visual tweaks and fixes the real experiment was conducted.