How to Induce a Physical and Virtual Rubber Hand Illusion

ALEXANDER KALUS, University of Regensburg, Germany
MARTIN KOCUR, University of Regensburg, Germany
JOHANNA BOGON, University of Regensburg, Germany
NIELS HENZE, University of Regensburg, Germany
VALENTIN SCHWIND, Frankfurt University of Applied Sciences, Germany

Understanding body ownership is essential when creating virtual reality (VR) applications using avatars. One of the most widely-used paradigm to investigate body ownership is the rubber hand illusion (RHI). When a real hand and a rubber hand are stroked synchronously, participants can experience the rubber hand as their own hand. Although the knowledge from RHI experiments in the real world is applied to when users embody avatars in VR, it is still unclear whether the illusory ownership of a virtual and physical body produce the same effects. In addition, conducting RHI studies in VR would allow gaining a range of novel experiments that are not possible in the real world. With this demonstration, we therefore present a system and approach to investigate the RHI in the real world and in VR.

CCS Concepts: • **Human-centered computing → HCI theory, concepts and models**.

Additional Key Words and Phrases: rubber hand illusion, virtual reality, virtual embodiment

ACM Reference Format:
Alexander Kalus, Martin Kocur, Johanna Bogon, Niels Henze, and Valentin Schwind. 2022. How to Induce a Physical and Virtual Rubber Hand Illusion. In *Mensch und Computer 2022 (MuC '22), September 4–7, 2022, Darmstadt, Germany*. ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3543758.3547512

1 INTRODUCTION AND BACKGROUND

In VR, users can experience a sense of ownership of a virtual body—a phenomenon known as the body ownership illusion (BOI) [15]. Previous work found that embodying an avatar—the digital self-representation of the user— increases the sense of presence [31] and improves depth perception [11]. Therefore, VR developers and researchers aim to induce a strong BOI of avatars to create a natural and realistic interaction in the virtual environment (VE). Thus, deeper knowledge of BOIs and the underlying mechanisms is vital to creating embodied VR experiences.

One of the key instruments to study BOIs [28] is the RHI paradigm that was first introduced by Botvinick and Cohen [6]. In the RHI, a rubber hand is placed on a table, anatomically congruent to a participant's hand, while the real hand is hidden. An experimenter then strokes both hands synchronously with a brush. The multisensory cues of seeing the rubber hand being touched and feeling a congruent touch on the own hand then cause the participant to experience the rubber hand as their own. Asynchronous stroking breaks the illusion, which is why it is frequently used as control condition [26]. The RHI has developed into a widely-used instrument to study the mechanisms underlying a BOI [26] and has been applied in clinical applications to treat psychiatric and neurological conditions [8, 14, 29].

Besides subjective measures to quantify the RHI using questionnaires (e.g., [23]), research also used the proprioceptive drift describing a shift in the perceived location of the participants' real hand [26]: If participants are instructed to localize their own hand after the RHI, they typically misperceive the location of the own hand towards the rubber hand (e.g., [6, 15, 26]). Furthermore, physiological responses in the real hand have been observed, such as decreased motor excitability [10], an increase in histamine reactivity [3], and a decrease in skin temperature [24].

From a human-computer interaction perspective, the question arises whether the effects of the RHI correspond to ownership sensations of avatars experienced in VR. VR enables users to experience a full-body illusion (FBI) of the avatar (e.g., [17, 19, 20]). When users perceive the avatar from a first-person perspective while experiencing visuo-tactile or visuo-motor stimulation using motion tracking technologies (i.e. moving the physical body and seeing the avatar mimicking the motion), they can feel ownership of the avatar and accept it as the own body in VR [28]. However, FBI and limb ownership (as occurring in the RHI) are two distinct illusions [4, 5, 22]. Additionally, FBIs induced by visuo-motor synchrony evoke a sense of agency of the virtual body that, in turn, can affect users' behavior and interaction [7, 18, 21]. Hence, it has not been validated whether a RHI and a BOI in VR produce comparable effects. A comparison is further complicated by the fact that in a FBI, the artificial body is in a congruent position, eliminating proprioceptive drift as a measurement.

Apart from experiments involving FBIs, a variety of VR studies have focused on virtual ownership of body parts such as virtual hands [16]. However, the induction methods deviated from the classic RHI procedure, e.g., by displaying the hand in an empty void [1], allowing participants to move the embodied hand using trackers [32], or applying tactile stimulation using a vibro-tactile stimulator, while presenting it visually as a moving ball [25]. These methodological inconsistencies and the lack of a physical RHI-setup acting as control condition limit a comparison to the effects of the RHI in the real world. A missing standardized method for the physical [26] and virtual RHI further complicates a comparison between the experiments. Hence, it is unclear if the principles gained from research on the RHI translate to VR, and whether and how illusory ownership of a virtual limb differs from illusory ownership of a physical limb.

A setup that enables to conduct RHI experiments in VR, as well as under equal conditions in the real world could shed light on differences between VR and the real world, as it allows to directly compare virtual body ownership and ownership of a physical entity. Additionally, the flexibility of VR environments that allow for systematically manipulating variables of the RHI paradigm (e.g., the appearance of the hand) would enable novel studies that increase our understanding of BOI or improve RHI-based therapies. With this demonstration, we present a system to systematically conduct the RHI in or outside of VR under equal conditions. Therefore, we implemented a VR environment, in which participants can experience the RHI procedure according to the original protocol [6]. The setting is designed to keep all factors between the RHI in VR and RHI in the real world constant. These include visual cues, synchronous and asynchronous visuo-tactile stimulation, social factors, as well as the assessment of proprioceptive drift and hand skin temperature.

2 SYSTEM

RHI Setup

As we set up the RHI in VR, as well as in a real environment, all objects mentioned in the following are placed in both, the real and the VE, unless stated otherwise. Their positions and dimensions therefore refer to both, the RHI in and outside VR and are depicted in Fig. 1.

Participants are seated at a table (surface of 140 cm × 70 cm, 76 cm in height), with the body and table midline being aligned. To the participant's right, there is a rubber model of a right human forearm, with the hand measuring 16 cm

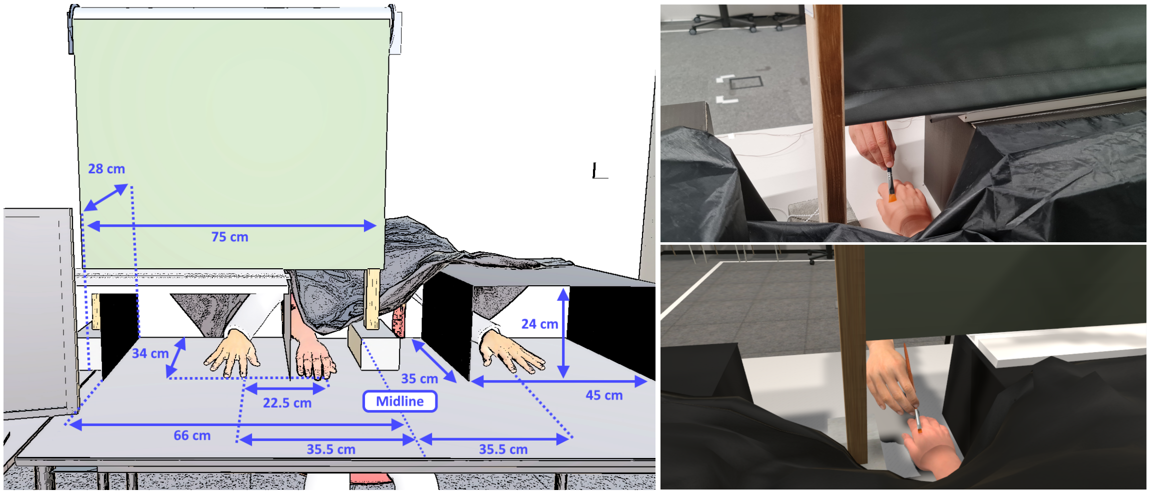

Fig. 1. Experimental setup (left) and the participants' view (right) for the RHI in the real world (top) and in VR (bottom).

from index fingertip to wrist. It is placed in an anatomically plausible posture, aligned at right angle to the participant's frontal plane. For the physical RHI, we use an artificial right forearm made from PVC-rubber as rubber hand (AFM-BLM Male flexible arms large hands medium arms, Hollands Wondere Wereld vof, the Netherlands) and designed the virtual version based on this model.

In VR, an avatar is placed at the location of the participant. To prevent unintended limb ownership of virtual body parts other than the rubber hand, both the participant and the avatar wear a cloth smock attached to the boxes to cover their visible body parts, as well as the upper part of the rubber hand. For the same reason, both of the participant's/avatar's hands are placed in two cardboard boxes in order to keep both hands out of sight. This has additional advantages if hand skin temperature is assessed, firstly as consistent conditions should be maintained for both hands and secondly, as it follows the approach, in which the temperature response was most evident [24]. The front, back, and bottom of the boxes are removed to ensure that they do not interfere with the participant's arms or the brush strokes.

An experimenter sits opposite the participant, controls the experiment, and applies the brush strokes during the RHI using flat paintbrushes (size 12). As social factors are assumed to affect the illusion [2, 9, 27], a roller blind (75 cm × 150 cm) is placed in front of the participant and lowered to conceal the experimenter, except for the hand stroking the rubber hand. Fig. 1 shows the participant's view during the virtual and physical RHI. A monitor on a separate table allows the experimenter to supervise the virtual scene.

For the assessment of the proprioceptive drift, an 80 cm × 25 cm × 1.6 cm board is located on top of the box that covers the right hand. After the stroking procedure, the board is pushed to the participant's left, hiding the rubber hand. It stops when it protrudes 7 cm over the table's midline (automatically in the virtual setting and by a cuboid on its bottom stopping against the cardboard box in the physical setting). A blanket attached to the board covers possible reference points. An 80 cm long scale is displayed on the board, parallel to the participants' frontal plane, on which the centimeter labels are replaced by 80 two-digit numbers. They are arranged in random order to prevent participants from using their indication from a prior trial as a reference for their new indication. For the same reason, we created four distinct scales, which vary in numbers and order. Participants are asked to state the number they believe the right index finger of the real hand is located. The proprioceptive drift is calculated by subtracting the position indicated by the participants from the actual index finger position.

Implementation of the Virtual RHI

For the virtual RHI we implemented the setting defined above as 3d environment using Unity 3D (v. 2019.2.1f1). The project files and the source code are available on github[1]. The virtual rubber hand was created using a 3d model from previous research on hand ownership [16, 30]. We edited its diffuse and normal maps to create a virtual replica of the physical rubber hand. The shader's smoothness was adjusted to achieve a slightly glossy surface similar to the physical rubber hand. Furthermore, we adapted and transformed the hand's rig to match the physical rubber hand.

Regarding the stroking procedure, we used Unity's cloth physics to animate the bristles. High-resolution real-time shadows from directional lights further enhance the appearance of brush strokes. Anti-Aliasing was set to 8x Multi Sampling to avoid pixelated shadows. In accordance with the physical setup, where the experimenter's hand is not covered by the roller blinds, a rigged realistic hand holding the brush was added to the 3d scene. Initially, we planned to track the brush to create a real-time stroking animation. Due to tracking inaccuracy causing offsets and asynchrony, we created a pre-defined stroking animation. The experimenter applies tactile stimulation in synchrony with this animation.

Technical Materials

The virtual RHI is designed to be experienced from a first-person perspective using a head-mounted display with head tracking enabled. In our tests, we used an HTC Vive Headset (HTC Corporation, Tayuan, Taiwan) connected to a PC running Windows 10, equipped with Intel i7 Processor, 16GB RAM, and an NVIDIA GeForce GTX 1080 graphics card. The experimenter uses a wireless controller (e.g., an HTC Vive Controller) to trigger the stroking animation and proprioceptive drift assessment. A monitor to the experimenter's left renders the scene in real-time enabling to synchronize the brush strokes with the rendered animation. In the physical RHI headphones can be used instead, to listen to a metronome app dictating the stroking speed. The experimenter can actuate a footswitch located under the table to log events such as the start and the end of the stroking procedure. The output of the foot controller is processed by a python script that writes a log file containing UNIX timestamps of the events.

Our apparatus allows the integration of measures obtaining physiological responses to the RHI. We, for example, incorporated a thermometer (TC-08 8-Channel USB Thermocouple Data Acquisition Module, Omega Engineering, USA) that can be used to record the skin temperature of the left and right hand. Therefore, T Type fast response insulated Thermocouples (Omega 5SRTC-TT-TI-20-2M) need to be taped on each hand. To increase measurement accuracy it is recommended to attach multiple thermocouples on each hand [13].

3 CONCLUSION AND FUTURE WORK

With this demonstration, we present a system to conduct RHI experiments in VR. The system includes a virtual RHI, as well as an identical physical RHI setup, to compare effects of a virtual and physical RHI. It is designed to ensure consistent visual, tactile, and social factors between both settings. Consequently, the setup allows to investigate, whether the RHI in the real world differs from the RHI in VR in terms of psychological and physiological responses. Future studies can utilize this apparatus to increase our understanding of body ownership. The virtual RHI provides a flexible

[1]https://github.com/a-kalus/virtual_rhi

tool to systematically manipulate factors contributing to the RHI. For instance, the setup can easily be adapted to explore virtual rubber hands, that burn [12], dynamically change [14], or depict realistic 3d scans of the participant's hand [25] to examine the role of individual characteristics in the mechanisms underlying a BOI.

REFERENCES

[1] Joanna Aldhous, Richard Hetherington, and Phil Turner. 2017. The Digital Rubber Hand Illusion. In *Proceedings of the 31st British Computer Society Human Computer Interaction Conference* (Sunderland, UK) *(HCI '17)*. BCS Learning & Development Ltd., Swindon, GBR, Article 59, 5 pages. https://doi.org/10.14236/ewic/HCI2017.59

[2] Tomohisa Asai, Zhu Mao, Eriko Sugimori, and Yoshihiko Tanno. 2011. Rubber hand illusion, empathy, and schizotypal experiences in terms of self-other representations. *Consciousness and Cognition* 20, 4 (2011), 1744–1750. https://doi.org/10.1016/j.concog.2011.02.005

[3] Nadia Barnsley, James H. McAuley, Rahul Mohan, Abishikta Dey, P. Thomas, and G. Lorimer Moseley. 2011. The rubber hand illusion increases histamine reactivity in the real arm. *Current Biology* 21, 23 (2011), R945–R946. https://doi.org/10.1016/j.cub.2011.10.039

[4] Olaf Blanke. 2012. Multisensory brain mechanisms of bodily self-consciousness. *Nature Reviews Neuroscience* 13, 8 (2012), 556–571. https://doi.org/10.1038/nrn3292

[5] Olaf Blanke and Thomas Metzinger. 2009. Full-body illusions and minimal phenomenal selfhood. *Trends in Cognitive Sciences* 13, 1 (2009), 7–13. https://doi.org/10.1016/j.tics.2008.10.003

[6] Matthew Botvinick and Jonathan Cohen. 1998. Rubber hands 'feel' touch that eyes see. *Nature* 391, 6669 (1998), 756. https://doi.org/10.1038/35784

[7] Niclas Braun, Stefan Debener, Nadine Spychala, Edith Bongartz, Peter Sörös, Helge H O Müller, and Alexandra Philipsen. 2018. The Senses of Agency and Ownership: A Review. *Frontiers in Psychology* 9 (2018), 535. https://doi.org/10.3389/fpsyg.2018.00535

[8] Oliver Christ and Miriam Reiner. 2014. Perspectives and possible applications of the rubber hand and virtual hand illusion in non-invasive rehabilitation: Technological improvements and their consequences. *Neuroscience & Biobehavioral Reviews* 44, 7 (2014), 33–44. https://doi.org/10.1016/j.neubiorev.2014.02.013

[9] Alyanne M. de Haan, Haike E. Van Stralen, Miranda Smit, Anouk Keizer, Stefan Van der Stigchel, and H Chris Dijkerman. 2017. No consistent cooling of the real hand in the rubber hand illusion. *Acta Psychologica* 179 (2017), 68–77. https://doi.org/10.1016/j.actpsy.2017.07.003

[10] Francesco Della Gatta, Francesca Garbarini, Guglielmo Puglisi, Antonella Leonetti, Annamaria Berti, and Paola Borroni. 2016. Decreased motor cortex excitability mirrors own hand disembodiment during the rubber hand illusion. *eLife* 5 (2016), e14972. https://doi.org/10.7554/eLife.14972

[11] Elham Ebrahimi, Andrew Robb, Leah S. Hartman, Christopher C. Pagano, and Sabarish V. Babu. 2018. Effects of Anthropomorphic Fidelity of Self-Avatars on Reach Boundary Estimation in Immersive Virtual Environments. In *Proceedings of the 15th ACM Symposium on Applied Perception* (Vancouver, British Columbia, Canada) *(SAP '18)*. Association for Computing Machinery, New York, NY, USA, Article 2, 8 pages. https://doi.org/10.1145/3225153.3225170

[12] Daniel Eckhoff, Cecilia Li-Tsang, Gladys Cheing, Alvaro Cassinelli, and Christian Sandor. 2021. Investigation of Microcirculatory Effects of Experiencing Burning Hands in Augmented Reality. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE Computer Society, Los Alamitos, CA, USA, 569–570. https://doi.org/10.1109/VRW52623.2021.00167

[13] A. Enander. 1984. Performance and sensory aspects of work in cold environments: a review. *Ergonomics* 27, 4 (1984), 365–378. https://doi.org/10.1080/00140138408963501

[14] Baland Jalal, Richard J McNally, Jason A Elias, Sriramya Potluri, and Vilayanur S Ramachandran. 2020. "Fake it till You Make it"! Contaminating Rubber Hands ("Multisensory Stimulation Therapy") to Treat Obsessive-Compulsive Disorder. *Frontiers in Human Neuroscience* 13 (2020), 414. https://doi.org/10.3389/fnhum.2019.00414

[15] Konstantina Kilteni, Antonella Maselli, Konrad P Kording, and Mel Slater. 2015. Over my fake body: body ownership illusions for studying the multisensory basis of own-body perception. *Frontiers in Human Neuroscience* 9 (2015), 141. https://doi.org/10.3389/fnhum.2015.00141

[16] Martin Kocur, Sarah Graf, and Valentin Schwind. 2020. The Impact of Missing Fingers in Virtual Reality. In *26th ACM Symposium on Virtual Reality Software and Technology* (Virtual Event, Canada) *(VRST '20)*. Association for Computing Machinery, New York, NY, USA, Article 4, 5 pages. https://doi.org/10.1145/3385956.3418973

[17] Martin Kocur, Florian Habler, Valentin Schwind, Paweł W. Woźniak, Christian Wolff, and Niels Henze. 2021. Physiological and Perceptual Responses to Athletic Avatars While Cycling in Virtual Reality. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 519, 18 pages. https://doi.org/10.1145/3411764.3445160

[18] Martin Kocur, Niels Henze, and Valentin Schwind. 2021. Towards an Investigation of Avatars' Sweat Effects during Physical Exertion in Virtual Reality. In *Mensch und Computer 2021 - Workshopband*, Carolin Wienrich, Philipp Wintersberger, and Benjamin Weyers (Eds.). Gesellschaft für Informatik e.V., Bonn, 3 pages. https://doi.org/10.18420/muc2021-mci-ws16-261

[19] Martin Kocur, Melanie Kloss, Valentin Schwind, Christian Wolff, and Niels Henze. 2020. *Flexing Muscles in Virtual Reality: Effects of Avatars' Muscular Appearance on Physical Performance*. Association for Computing Machinery, New York, NY, USA, 193–205. https://doi.org/10.1145/3410404.3414261

[20] Martin Kocur, Philipp Schauhuber, Valentin Schwind, Christian Wolff, and Niels Henze. 2020. The Effects of Self- and External Perception of Avatars on Cognitive Task Performance in Virtual Reality. In *26th ACM Symposium on Virtual Reality Software and Technology* (Virtual Event, Canada) *(VRST '20)*. Association for Computing Machinery, New York, NY, USA, Article 27, 11 pages. https://doi.org/10.1145/3385956.3418969

[21] Martin Kocur, Valentin Schwind, and Niels Henze. 2019. Utilizing the Proteus Effect to Improve Interactions using Full-Body Avatars in Virtual Reality. In *Mensch und Computer 2019 - Workshopband*. Gesellschaft für Informatik e.V., Bonn, 566–567. https://doi.org/10.18420/muc2019-ws-584

[22] Ryota Kondo, Yamato Tani, Maki Sugimoto, Masahiko Inami, and Michiteru Kitazaki. 2020. Scrambled body differentiates body part ownership from the full body illusion. *Scientific Reports* 10, 1 (2020), 5274. https://doi.org/10.1038/s41598-020-62121-9

[23] M. Longo, Friederike Schüür, Marjolein P. M. Kammers, M. Tsakiris, and P. Haggard. 2008. What is embodiment? A psychometric approach. *Cognition* 107, 3 (2008), 978–998.

[24] G. Lorimer Moseley, Nick Olthof, Annemeike Venema, Sanneke Don, Marijke Wijers, Alberto Gallace, and Charles Spence. 2008. Psychologically induced cooling of a specific body part caused by the illusory ownership of an artificial counterpart. *Proceedings of the National Academy of Sciences* 105, 35 (2008), 13169–13173. https://doi.org/10.1073/pnas.0803768105

[25] Maria Pyasik, Gaetano Tieri, and Lorenzo Pia. 2020. Visual appearance of the virtual hand affects embodiment in the virtual hand illusion. *Scientific Reports* 10, 1 (2020), 5412. https://doi.org/10.1038/s41598-020-62394-0

[26] Martin Riemer, J. Trojan, Marta Beauchamp, and X. Fuchs. 2019. The rubber hand universe: On the impact of methodological differences in the rubber hand illusion. *Neuroscience & Biobehavioral Reviews* 104 (2019), 268–280.

[27] Marieke Rohde, Andrew Wold, Hans-Otto Karnath, and Marc O. Ernst. 2013. The Human Touch: Skin Temperature during the Rubber Hand Illusion in Manual and Automated Stroking Procedures. *PLOS ONE* 8, 11 (2013). https://doi.org/10.1371/journal.pone.0080688

[28] Daniel Roth and Marc Erich Latoschik. 2020. Construction of the Virtual Embodiment Questionnaire (VEQ). *IEEE Transactions on Visualization and Computer Graphics* 26, 12 (2020), 3546–3556. https://doi.org/10.1109/TVCG.2020.3023603

[29] Michael Schaefer, Claudia Denke, Ivayla Apostolova, Hans-Jochen Heinze, and Imke Galazky. 2016. A Case of Right Alien Hand Syndrome Coexisting with Right-Sided Tactile Extinction. *Frontiers in Human Neuroscience* 10 (2016), 105. https://doi.org/10.3389/fnhum.2016.00105

[30] Valentin Schwind, Pascal Knierim, Lewis Chuang, and Niels Henze. 2017. *"Where's Pinky?": The Effects of a Reduced Number of Fingers in Virtual Reality*. Association for Computing Machinery, New York, NY, USA, 507–515. https://doi.org/10.1145/3116595.3116596

[31] Richard Skarbez, Frederick P. Brooks, Jr., and Mary C. Whitton. 2017. A Survey of Presence and Related Concepts. *ACM Comput. Surv.* 50, 6, Article 96 (nov 2017), 39 pages. https://doi.org/10.1145/3134301

[32] Ye Yuan and Anthony Steed. 2010. Is the rubber hand illusion induced by immersive virtual reality?. In *2010 IEEE Virtual Reality Conference (VR)*. IEEE, Waltham, Massachusetts, USA, 95–102. https://doi.org/10.1109/VR.2010.5444807