The Rubber Hand Illusion in Virtual Reality and the Real World - Comparable but Different

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ABSTRACT

Feeling ownership of a virtual body is crucial for immersive experiences in VR. Knowledge about body ownership is mainly based on rubber hand illusion (RHI) experiments in the real world. Watching a rubber hand being stroked while one's own hidden hand is synchronously stroked, humans experience the rubber hand as their own hand and underestimate the distance between the rubber hand and the real hand (proprioceptive drift). There is also evidence for a decrease in hand temperature. Although the RHI has been induced in VR, it is unknown whether effects in VR and the real world differ. We conducted a RHI experiment with 24 participants in the real world and in VR and found comparable effects in both environments. However, irrespective of the RHI, proprioceptive drift and temperature differences varied between settings. Our findings validate the utilization of the RHI in VR to increase our understanding of embodying virtual avatars.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**.

KEYWORDS

rubber hand illusion, virtual reality, avatars, body ownership illusion, proprioceptive drift, disownership

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1 INTRODUCTION

Virtual reality (VR) enables users to experience a sense of ownership of a virtual body—a phenomenon known as the body ownership illusion (BOI). Designers and researchers of VR applications commonly use avatars—the digital self-representation of the user—to provide users with a virtual body in VR and create embodied experiences (c.f., [34, 39]). Hence, the sense of having a virtual body in VR contributes to an enhanced and more realistic user experience [35, 67]. For this reason, understanding BOIs and the underlying mechanisms is important for the design of avatars and immersive VR experiences. Our knowledge about body ownership is based on the seminal RHI, which has evolved into a key instrument for investigating the embodiment of artificial limbs and significantly contributed to a better understanding of human cognition and bodily awareness [52].

In 1998, Botvinick and Cohen [6] demonstrated that humans can experience an artificial limb—a *rubber hand*—as if it was their own hand. The RHI is a illusory sensation of embodying the rubber hand and induced by multisensory conflicts. When the subjects' real hand, which is hidden from view, and the rubber hand are stroked at the same time while the subjects can see the rubber hand, after some time they start to perceive the artifical limb as being a part of their own body. As a result, subjects perceive the own hand to be closer to the rubber hand. This phenomenon is known as *proprioceptive drift*.

There is also empirical evidence that the RHI evokes physiological responses. Interestingly, Moseley et al. [47] revealed that when participants experienced ownership of the rubber hand, the skin temperature of the own hand decreased. As a drop in temperature could also be found in neurological disorders, e.g., patients suffering from somatoparaphrenia have the feeling that their affected limbs belong to someone else [75], the authors concluded that these findings are associated with a *disownership* of the real hand. However, many other studies were not able to replicate these and other related results using the RHI paradigm [8, 10, 16, 21, 42, 54, 58]. For this reason, effects on skin temperature caused by the RHI are highly controversial [10].

The importance of the RHI is not limited to the understanding of human perception. Understanding the RHI has implications for the design of immersive virtual environments (VEs) in general and avatar creation in particular. Consequently, the knowledge from

RHI experiments in the real world is transferred into VR to make users experiencing ownership of virtual avatars [62]. For years, designers and researchers have adopted the principles that govern the induction of the RHI to induce BOIs in VR. Previous work found, for example, that users feel ownership of virtual hands when they see the virtual hands from a first-person perspective while both the virtual and real limbs are synchronously stroked [63]. Although it is known that users can even feel ownership of full-body avatars in VR (e.g., [34, 37]), there is currently no empirical evidence that the effects caused by ownership illusions in the real world are the same as in virtual worlds.

A comparison between BOIs in both environments would validate that the principles that apply for BOIs in the real world translate to VR. Such a validation is important for designers and researchers of VR applications as it provides insights into whether there are differences between virtual and real bodily illusions that have to be considered during induction. For example, effects of technological latency during stroking in VR or a decreased realism of a VE can cause different degrees of BOIs compared to the real world that have to be compensated by designers and researchers, e.g., adapting induction procedures such as slower, longer, or firmer stroking [52]. The RHI is a promising paradigm for this to explore as it allows to induce an ownership illusion over a physical rubber hand in the real word and it can be transferred into VR to create the illusory sensation of embodying a virtual rubber hand.

In this paper, we conducted a study with 24 participants who experienced the RHI in the real world as well as in VR using a virtual replica of the real environment. We found that the proprioceptive drift was generally higher in VR compared to the real world. Our results also revealed effects on the skin temperature of the own hand. This implies that the RHI can induce temperature changes. We discuss our findings in the light of theories on psychological disownership of real body parts and provide implications for the virtual embodiment of avatars in VR. This work evaluates an experimental setting to systematically induce the RHI in reality and in VR and validates the utilization of the RHI in VR. Hence, we show that researchers and designers can leverage VR technology to perform classical RHI experiments to further study the cognitive processes underlying BOIs.

2 RELATED WORK

Our work is based on a growing body of work demonstrating perceptual and physiological effects caused by the RHI. In this section, we first provide an overview of RHIs and the effects on humans experiencing artificial limbs as their own. Afterwards, we summarize previous work that cover RHIs in immersive virtual settings.

2.1 Rubber Hand Illusions

First demonstrations of an effect similar to the RHI were already published in 1937 by Tastevin [68], who reported that people could experience a plastic finger as their own finger, which was concealed from view using a piece of cloth. After the seminal RHI from 1998 [6] ignited the research interest in such perceptual illusions, many researchers across various fields used such perceptual illusions to learn about human cognition. There are some requirements that have to be met to be able to induce the RHI [30].

Typically, researchers apply synchronous visuo-tactile stimulations creating a synchrony between the seen stroking of the rubber hand and the felt stroking of the real hand (e.g., [2, 6, 72]). Slater et al. [63], for example, used a soft ball attached to a wand to tap and stroke the participants' arm. Asynchronous stroking, however, destroys the illusion, e.g., a temporal delay between stroking of the rubber hand and real hand [52], as the brain is not able to integrate the cues from different sensory modalities into a unified percept [23]. Kalckert and Ehrsson [26] applied synchronous visuo-motor stimulations by enabling the participants to move a finger of the rubber hand. This resulted in a visuo-motor synchrony so that participants felt their own finger movements and synchronously saw the finger of the rubber hand moving [11]. Kalckert and Ehrsson [27] showed that the illusion is equally strong for tactile stimulations or active movements. Giummarra et al. [18] even demonstrated that the mere observation of a rubber hand in an anatomical plausible position and posture is sufficient to invoke the RHI; however, the illusion can be enhanced through visuo-motor contingencies [18]. Furthermore, Kilteni et al. [30] concluded that it is necessary for the illusion to occur that the artificial limb has to satisfy to some extent semantic constraints, e.g., it has to conform to humans' anatomical structures [71]. Non-corporeal objects that violate human anatomy such as checkerboards cannot create a sense of embodiment [81].

Riemer et al. [52] provided a summary of sophisticated approaches that are used to quantify the RHI. Validated questionnaires are a common method to assess the experienced RHI. Different subscales and items, e.g., "it seemed like the rubber hand was my hand" or"it seemed like the rubber hand belonged to me" [44], have been used to measure the degree of the felt embodiment of the rubber hand. Besides, perceptual responses such as the proprioceptive drift were assessed during or immediately after the RHI [51, 72]. The proprioceptive drift describes the illusory shift in location of the own hand towards the rubber hand, so that participants perceive their own hand being closer to the rubber hand. Further objective measures for quantifying the RHI are physiological responses.

While various studies also used arousal-related metrics to assess physiological reactions to a threatened rubber hand (see [13, 30, 52]), Moseley et al. [47] were the first demonstrating that embodying a rubber hand caused a drop in temperature in the real hand. The authors argued that these findings indicate that a process of disembodiment of the real hand occurs during the RHI. Moseley et al. [46] reported a possible explanation for this phenomenon and concluded that the blood flow to the "disembodied" hand was reduced while embodying the rubber hand. In line with these findings, Kammers et al. [29] modulated the extent of the RHI by manipulating the temperature of the participants' hand. Cooling their hand increased the strength of the RHI whereas warming decreased its strength. Furthermore, Salomon et al. [56] induced a full-body illusion by synchronously stroking the participants' back and legs. Accordingly, the authors found a drop in skin temperature across different body parts.

Another study found that the histamine reactivity of the own hand was increased during the RHI, which is an indicator for a decreased response of the immune system [5]. Folegatti et al. [16], however, hypothesized that changes in skin temperature originate from the visuo-proprioceptive conflict induced by the RHI instead of a process of disownership. The authors did not use an artificial limb such as a rubber hand but, instead, they shifted the position of the real hand by 7.5 cm using prismatic goggles. By doing so, they still slowed down tactile sensitivity and induced a proprioceptive drift even if it was the own hand. On the contrary, Hohwy and Paton [24] could show a decreased skin temperature using a rubber hand which was co-located with the real hand..

Even if these intriguing findings suggest that the RHI can affect unconscious and autonomic bodily functions such as thermoregulation, many researchers call such effects into question as they could not be replicated in various other studies [9, 10, 20, 48, 54, 69]. As such, de Haan et al. [10] and Rohde et al. [54] discussed potential factors that confound effects on skin temperature during the RHI, e.g., the speed, force and duration of stroking, lighting conditions, and the characteristics of the experimenter. Hence, it still remains unknown whether there is a causal relationship between the experienced embodiment of the rubber hand, the disownership of the real hand, and the resulting effects on skin temperature.

2.2 Bodily Illusions in VR

Research from human-computer interaction (HCI) applies the knowledge from experiments inducing bodily illusions to create vivid and effective VR experiences using virtual avatars [35, 38, 40, 41, 62]. Slater et al. [63] transferred the concept of the RHI into VR by tapping and stroking the participants' real arm using a soft ball and accordingly displaying this tactile stimulation by a virtual soft ball on a virtual arm rendered on a large display in front of the participants. The authors reported that the participants could experience a sense of embodiment over the virtual arm.

Similar effects were revealed in another study where the authors generated a virtual arm illusion [64]. Likewise, Yuan and Steed [80] wondered whether the RHI can be induced by immersive VR. In contrast to the "classical" RHI paradigm, the participants could move their virtual arms while being embodied in a full-body avatar. The embodiment of a full-body avatar with features and characteristics that deviate from the users' real physical body can evoke perceptual and attitudinal changes [34, 36, 39, 79]. Thus, it is impossible to isolate the effects caused by the limb ownership of one body part, such as a virtual arm, from effects caused by the body ownership of an entire body, which addresses the bodily self as a whole [7].

Another series of studies showed that users can embody virtual hands with a reduced amount of fingers [33, 59], with a different gender [60] as well as with a non-human appearance such as robot hands [61]. As the authors wanted to create a natural and familiar interaction with the VE, the participants' arm and hand movements were tracked using motion capture systems and transferred onto the animation of the virtual hands. This is in line with Ma et al. [45] or Ariza et al. [1], who also used hand tracking technology to induce a virtual hand illusion. Hence, instead of a passive induction through visuo-tactile synchrony, the authors applied an active induction through visuo-motor synchrony [57]. As bodily illusions are modulated by visuo-tactile, visuo-motor and visuo-proprioceptive cues [30], the type of stimulation influences the experienced embodiment.

Similar to real world experiments, perceptual, behavioral and physiological responses are used for quantifying the RHI [30]. Previous work found that users instinctively reacted to a virtual knife stabbing the embodied virtual hand by moving the threatened hand out of the way to avoid being injured [19]. Kocur et al. [33] also showed emotional responses such as phantom pain when removing single fingers of the virtual hand. Tieri et al. [70] investigated the hand temperature and showed that a first-person perspective was sufficient to induce a limb ownership illusion of a virtual arm with different appearances, e.g., anthropomorphic or wooden. The authors found an increase in hand temperature for all types of arm appearances. However, the increase was lower during the embodiment of the anthropomorphic virtual arm. These results suggest that the effects on hand temperature are modulated by the vividness of the ownership illusion.

In a review about bodily illusions, Braun et al. [7] concluded that users can even experience a sense of ownership of full-body avatars. Previous work induced a body ownership of avatars, for example, with a different muscular [37] and athletic [34] appearance or with a different age [3, 4, 39, 50]. Overall, in all these studies the experimental design did not involve a control condition consisting of an artificial arm illusion or even full-body illusion performed in the real world, e.g., using a rubber hand or a mannequin [49].

2.3 Summary

The RHI can cause perceptual and physiological changes, such as an elevated skin conductance response [13] or increased heart rate [65]. While some studies even revealed that the embodiment of a rubber hand causes a drop in skin temperature of the own hand [24, 29, 47, 56, 73], others could not show such thermal reactions [9, 10, 20, 48, 54, 69]. Designers and researchers of VR applications apply the knowledge gained from BOIs in the real world to induce ownership of virtual avatars. However, a systematic comparison between the effects caused by BOIs in the real world and BOIs in VR has not been conducted yet.

3 METHOD

To find out whether the RHI induced in the real world differs from a RHI in VR and compare the magnitude of effects between both environments, we induced a RHI based on the experimental procedure by Moseley et al. [47] in both environments. We further explored whether the RHI can cause skin temperature changes of the own hand.

3.1 Study Design

We conducted a study using a within-subjects design with two independent variables. To deteremine whether the effects of the RHI induced in the real world differ from a RHI induced in VR, we used the independent variable ENVIRONMENT with the two levels *real* and *VR*. In the *real* condition, the RHI was conducted in the real world whereas in the *VR* condition, the RHI was conducted in VR using a virtual replica of the real environment (see Figure 1). As previous work found that it is crucial that the real hand and the rubber hand are touched at the same time to induce the RHI and that temporal deviations between the seen and the felt touch stop the illusion from occurring [30], we systematically manipulated the

Figure 1: RHI performed in the real world and in VR (top), and the participants' view of the real environment and the VE (bottom). Participants saw the rubber hand being stroked while their real hands were hidden from view.

synchrony of the applied tactile and visual cues to modulate the RHI. Hence, we used the independent variable Synchrony with the two levels *synchronous* and *asynchronous*.

In the *synchronous* condition, we synchronously stroked the participants' real hand and the rubber hand in time and at the correct position so that the participants saw and felt the stroking congruently. In the *asynchronous* condition, we created a temporal delay of approximately 5 s (duration of one stroke) between the stroking on the rubber hand and the real hand by stroking both of them alternately. This temporal delay between the visual perception and the tactile perception of the stroking should prevent the illusion from occurring [6, 15]. Hence, the asynchronous stimulation served as a control condition allowing to control for effects caused by the embodiment of the rubber hand. To reduce order effects, we counterbalanced the order of the conditions employing all possible permutations.

3.2 Measures

We took multiple measures to determine the effects of the independent variables. We assessed the proprioceptive drift and used a RHI questionnaire [44] for quantifying the RHI. Additionally, we measured the skin temperature of both hands during the entire course of each condition to analyze how the skin temperature evolves across time. As handedness does not modulate the extent of the RHI [66], we determined the right hand to be the stimulated hand, which was stroked and hidden from view during the procedure. The left hand was used as a control hand (unstimulated hand) and was neither touched nor seen during the RHI procedure.

3.2.1 Proprioceptive Drift. We measured the proprioceptive drift, which describes a shift of the stimulated hand's perceived location towards the rubber hand. A higher proprioceptive drift indicates a stronger RHI [72]. To assess this illusory drift, we used the ruler technique, which is a widely used strategy to quantify the proprioceptive drift [52]. After each condition, we placed a ruler above the participants' right hand (stimulated) and the rubber hand, which were both hidden and could not be seen during the assessment of the proprioceptive drift. For the RHI in VR, we used a virtual ruler with the same scales as the physical ruler. We then asked the participants to verbally indicate the number that is directly above their own index finger.

3.2.2 RHI Questionnaire. We asked the participants to fill the RHI questionnaire designed by Longo et al. [44] for quantifying the experienced RHI. The questionnaire consists of seven-point Likert items ranging from "strongly disagree" to "strongly agree". The items reflect five dimensions: *embodiment of rubber hand*, *loss of own hand*, *movement*, *affect* and *deafference*. For the *VR* condition, we changed the term "rubber hand" into "virtual rubber hand". At the end of the questionnaire, we added an additional item which should explore whether the participants perceived any change in skin temperature in the right hand (stimulated). Accordingly, we used a seven-point Likert item ranging from "cooling" to "heating".

In all conditions, the questionnaire was administered on a desktop computer.

3.2.3 Skin Temperature. We continuously measured the participants' skin temperature on their right and left hand to control whether potential effects on skin temperature are limb-specific. If effects on the skin temperature originate from the embodiment of the rubber hand, they should not occur on the unstimulated hand [47]. We therefore evaluated the time course of the temperature difference between the right hand (stimulated) and the left hand (unstimulated) across the entire stroking procedure. To calculate the temperature difference between both hands, we subtracted the temperature on the left hand (unstimulated) from the temperature on the right hand (stimulated): $\Delta t = t(\textit{stimulated hand}) - t(\textit{unstimulated hand})$. A negative difference indicates a lower temperature in the right hand (stimulated) than in the left hand (unstimulated). We therefore hypothesize that the negative difference between both hands increase over time due to a decrease in temperature of the right hand (stimulated). Additionally, we also analyzed the absolute skin temperature of the right hand (stimulated) and the left hand (unstimulated) across time.

3.3 Apparatus

We employed the same apparatus as proposed by Kalus et al. [28]. We used two black cardboard boxes (45cm x 35cm x 23cm) with cut holes placed on a table in front of the participants to hide their hands (both the right and the left hand) during the RHI. The male experimenter sat opposite the participants and used two common paintbrushes to stroke the rubber hand and the participants' right hand. The experimenter also used in-ear headphones and a metronome application running on a smartphone for pacing each stroke.

As prior investigations found that seeing the experimenter during the stroking may influence the experience of touch [10, 17], we used a window roller blind mounted on two wooden bars to avoid that the participants could see the experimenter during the RHI. Thus, the participants only saw the experimenter's hand stroking the rubber hand. A life-sized rubber model of a right human arm (AFM-BLM Male flexible arms large hands medium arms, Hollands Wondere Wereld vof, the Netherlands) was placed in front of the participants in an anatomically plausible posture. The participants wore a large black hairdressing cape to cover the forearm of the rubber model and to ensure that the participants could not see their own body parts during the RHI.

To measure the participants' skin temperature, we used a professional thermometer module with a sampling rate of 10 Hz and a resolution of 20 bit (TC-08 8-Channel USB Thermocouple Data Acquisition Module, Omega Engineering, USA). We used four insulated T-thermocouples (Fast response insulated thermocouple with connectors: 5SRTC-TT-TI-20-2M, Omega, USA) to assess the skin temperature on each hand. To increase measurement accuracy and compensate for a potential malfunction of a thermocouple, we attached two thermocouples on the back of the right hand and another two on the back of the left hand using a common adhesive tape. To assess the proprioceptive drift, we used a printed paper ruler (centimeter ruler for A3 paper, 80 cm) placed on a wooden board. As the proprioceptive drift was measured four times in total (once per condition), we used four rulers with different scales to avoid biased answers caused by the recall of previous responses and memory effects. Each ruler was only used once per experiment and was randomly chosen for the conditions. Additionally, the experimenter used a USB foot switch to log UNIX timestamps for determining the start and end of each condition.

To be able to compare the RHI conducted in the real world and the RHI in VR, we designed a virtual replica of the real environment with the identical experimental setup as in reality (see Figure 1). We used the game engine Unity3D (v. 2019.2.1f1) to develop the VR application. We designed a virtual rubber hand using a rubber shader. We also designed a realistic virtual hand holding a paintbrush, which represented the experimenter's hand stroking the virtual rubber hand. To avoid tracking errors and reduce temporal deviations between the applied tactile and visual cues due to the latency of the VR system, we created a stroking animation to precisely simulate the stroking of the experimenter. A screen was placed next to the experimenter displaying the participants' view of the VE. This allowed the experimenter to align the stroking of the real hand to the stroking of the virtual hand in the *VR* condition.

We used an HTC Vive head-mounted display (HMD) (HTC Corporation, Tayuan, Taiwan) with a wide horizontal field of view of 100° and a spatial resolution of 1080 × 1,200 pixels per eye. In line with the real environment, their virtual body was covered by a cloth-simulated cape. The VR application ran on a desktop PC (MS-Windows 10, Intel i7-8750H, 16GB RAM, NVIDIA GeForce GTX 1060 graphics card). The project files and the source code of the VR prototype are available on github[1].

3.4 Participants

We recruited 24 participants (14 male and 10 female) through our university's mailing list and public forums. Their age ranged from 19 to 29 years (M = 23.91 SD = 2.45). All of them had either normal or corrected-to-normal vision. None of them reported any pain in the upper limbs (shoulder, arm or hand region) before the study. One participant was left-handed. Participants received course credits for participating in the study. They were informed that they could withdraw or discontinue the experiment at any time without penalty.

3.5 Procedure

After welcoming the participants, we explained the procedure of the study. We then asked them to sign an informed consent form and to complete the demographics questionnaire. Afterwards, the participants sat at the table at a predefined position 37.5 cm from the body's midline (coronal plane) to the rubber hand. In the *VR* condition, the experimenter helped the participants with putting on the HMD, adjusted it to their head, and calibrated the inter-pupil distance if necessary. Afterwards, the participants put their right and left hand into the cardboard boxes to keep both hands out of view.

The experimenter placed the hairdressing cape over the participants' shoulders to cover their body and the forearm of the rubber hand model. The experimenter then took a seat opposite the participants and attached the thermocouples on both of their

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

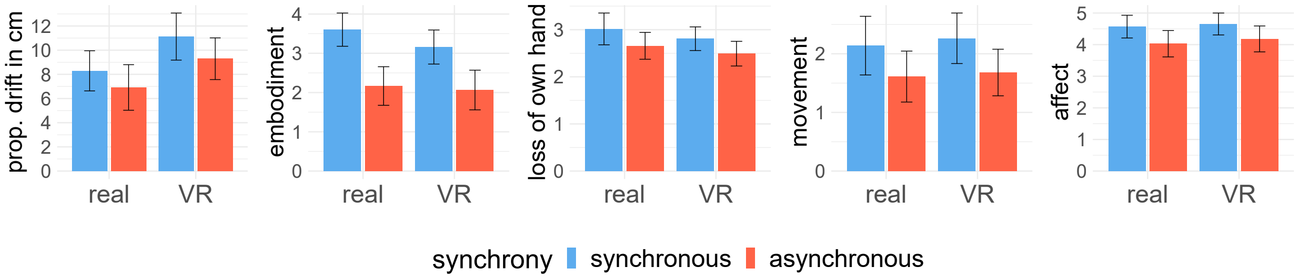

Figure 2: Mean values of the proprioceptive drift (cm) and the dimensions of the RHI questionnaire embodiment, loss of own hand, movement, and affect for the RHI performed in the real world and in VR. The error bars show the 95% confidence interval.

hands using tape. The experimenter precisely positioned the participants' hands at a fixed location marked with tape strips on the table. The participants were asked to keep their hands still during the procedure. The tip of the right index finger was 22.5 cm from the rubber hand's tip of the index finger. This distance conforms to the mean of distances used in a series of studies by Moseley et al. [47]. Before a trial started, the roller blind was lowered to ensure that the participants could not see the experimenter except for the hand stroking the rubber hand.

The experimenter started the conditions by pressing the foot switch and beginning to stroke. Each stroke started from the wrist along the index finger to the finger tip resulting in a stroking distance of ~15 cm. In line with current recommendations about stroking velocity [52], we used a velocity of ~3 cm/s so that each stroke lasted ~5 s. After a stroke, the experimenter immediately repositioned the brushes at the wrist and started the next stroke. In the *VR* condition, a stroking animation was displayed so that the experimenter only stroked the real hand aligned to the animation.

After three minutes of stroking per condition, the proprioceptive drift was assessed. Therefore, the roller blind was rolled up and the ruler attached on a wooden board was placed above the participants' right hand as well as the rubber hand. We asked the participants to verbally indicate the number that is directly above their own index finger. In the *VR* condition, the experimenter triggered an event using the HTC Vive controller, which simulated the real-world setting by automatically rolling up the virtual roller blind and placing the virtual ruler at the same position in the VE.

The experimenter then removed the thermocouples, and helped the participants with taking off the hairdressing cape and the HMD. Afterwards, the participants completed the RHI questionnaire on a desktop computer. This procedure is repeated for each condition. The study took approximately 60 minutes per participant in total.

4 RESULTS

Our measures consist of parametric data. We used Shapiro-Wilk tests to determine the assumption of normal distribution of the proprioceptive drift and the scores of the RHI questionnaire (all $p > .05$). As skin temperature is normally distributed across the population, we also assume a normal distribution of the skin temperature data.

4.1 Proprioceptive Drift

A 2(Environment:*real* vs. *VR*) x 2(Synchrony: *synchronous* vs. *asynchronous*) ANOVA revealed a significant main effect of Environment, $F(1, 23) = 14.426$, $p < .001$, $\eta_p^2 = .385$, on the proprioceptive drift. Participants showed a generally larger proprioceptive drift in VR compared to the real environment (10.2cm vs. 7.6cm). There was also a significant main effect of Synchrony, $F(1, 23) = 6.591$, $p = .017$, $\eta_p^2 = .222$, indicating a higher proprioceptive drift in the synchronous conditions compared to the asynchronous conditions (9.7 cm vs. 8.1 cm). However, there was no significant interaction effect of Environment × Synchrony, $F(1, 23) = .139$, $p = .712$, $\eta_p^2 = .006$. The non-significant interaction effect Environment × Synchrony revealed by the ANOVA does not automatically confirm the hypothesis that the difference in proprioceptive drift between the *synchronous* condition and the *asynchronous* condition is comparable between environments.

To quantify the comparability of the effects between VR and the real world, we calculated a Bayesian *t*-test on the differences between the proprioceptive drift in the *synchronous* condition and the *asynchronous* condition ($\Delta PropDrift = PropDrift_{sync} - PropDrift_{async}$) for both settings [77]. This revealed a Bayes factor of $BF_{01} = 4.371$, indicating that the data is 4.37 times more likely under the null hypothesis postulating identical RHI effects on proprioceptive drift for VR and the real environment ($\Delta PropDrift_{VR} = \Delta PropDrift_{real}$) than under the alternative hypothesis that postulates different effects ($\Delta PropDrift_{VR} \neq \Delta PropDrift_{real}$). Figure 2 depicts the mean ratings of the proprioceptive drift.

4.2 RHI Questionnaire

We performed 2(Environment:*real* vs. *VR*) x 2(Synchrony: *synchronous* vs. *asynchronous*) ANOVAs on each dimension of the RHI questionnaire. Figure 2 shows the mean ratings for the dimensions *embodiment*,*loss of own hand*, *movement*, and *affect*.

We did not find any significant effect of Environment on the dimensions of the RHI questionnaire (all $p > .05$). However, we found a significant effect of Synchrony on the dimensions *embodiment of the rubber hand*, $F(1, 23) = 43.443$, $p < .001$, $\eta_p^2 = .653$, *loss of own hand*, $F(1, 23) = 9.224$, $p = .005$, $\eta_p^2 = .286$, *movement*, $F(1, 23) = 7.951$, $p = .009$, $\eta_p^2 = .256$, and *affect*, $F(1, 23) = 21.371$, $p < .001$, $\eta_p^2 = .481$. We did not find any significant interaction

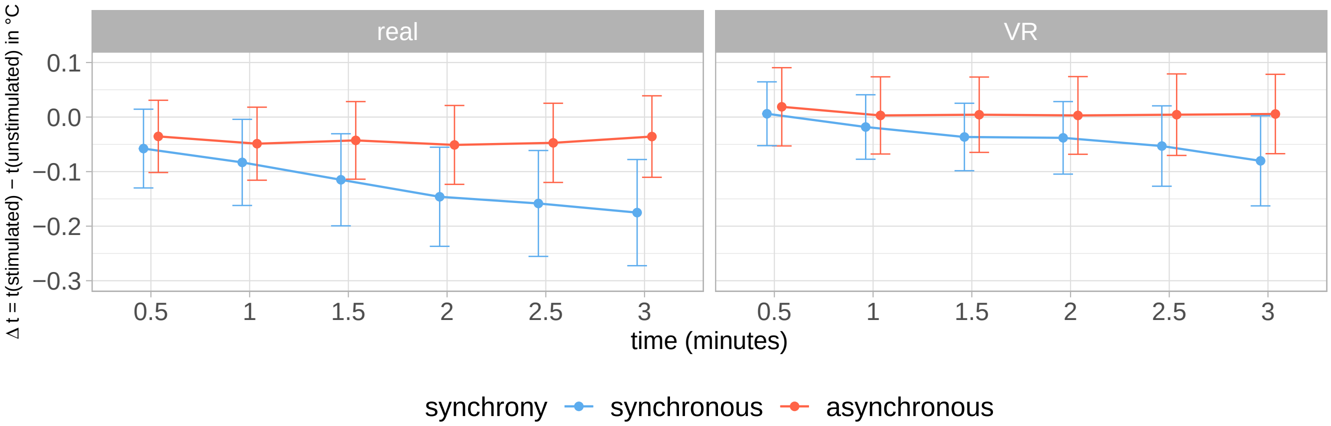

Figure 3: Average temperature difference (Δt) between the right (stimulated) and left hand (unstimulated) per 30 seconds during the RHI in the real world and in VR for synchronous and asynchronous stroking. The error bars show the standard error.

effect Environment × Synchrony on the dimensions of the RHI questionnaire. The calculated Bayes factor showed anectodal to moderate evidence ($BF_{01} >= 2.162$ and $BF_{01} <= 4.589$) that the data is more likely under the null hypothesis postulating identical RHI effects on the dimensions of the RHI questionnaire for VR and the real environment. Figure 2 depicts the average proprioceptive drift and the mean ratings of the RHI questionnaire.

4.2.1 Correlation Analysis of the Proprioceptive Drift and the Dimensions of the RHI Questionnaire. To test whether there is a relationship between the proprioceptive drift and the experienced embodiment of the rubber hand, we performed a Pearson's correlation analysis of the dimensions of the RHI questionnaire and the proprioceptive drift in the *synchronous* conditions. We did not find a significant relationship between proprioceptive drift and the dimensions *embodiment of the rubber hand*, *loss of own hand*, *movement* and *deafference* of the RHI questionnaire (all $p > .05$). However, there was a significant positive correlation between the proprioceptive drift and the dimension *affect*, $r(46) = .333$, $p = .020$.

4.3 Skin Temperature

As previous work found that a drop in skin temperature was caused by the embodiment of the rubber hand and, thereby, only occurred in the stimulated hand and not in the unstimulated hand [47], we evaluated the time course of the temperature difference between the right hand (stimulated) and the left hand (unstimulated) across the entire stroking procedure (see Figure 3). Additionally, we analyzed the absolute skin temperature of the right (stimulated) and left hand (unstimulated) across time (see Figure 4). In line with Moseley et al. [47], we calculated 30-second time intervals and included the factor TIME with six levels in the statistical analyses. Hence, we performed 2(Environment:*real* vs. *VR*) x 2(Synchrony: *synchronous* vs. *asynchronous*) x 6(Time: *0.5* vs *1* vs *1.5* vs *2* vs *2.5* vs *3*) ANOVAs to analyze the skin temperature across time.

4.3.1 Skin Temperature Difference between Both Hands. We did not find a significant main effect of Environment, $F(1, 23) = .581$, $p = .453$, $\eta_p^2 = .024$, of Synchrony, $F(1, 23) = .704$, $p = .409$, $\eta_p^2 = .029$ and of Time, $F(5, 115) = 2.074$, $p = .073$, $\eta_p^2 = .082$. However, we found a significant interaction effect of Synchrony × Time, $F(5, 115) = 4.829$, $p < .001$, $\eta_p^2 = .173$, indicating that the skin temperature differences between both hands over the course of time depended on the synchrony of stroking. We did not find interaction effects of Environment × Synchrony, $F(1, 23) = .048$, $p = .827$, $\eta_p^2 = .002$, of Environment × Time, $F(5, 115) = .185$, $p = .967$, $\eta_p^2 = .007$, as well as of Environment × Synchrony × Time, $F(5, 115) = .360$, $p = .874$, $\eta_p^2 = .015$. Bonferroni-corrected post-hoc comparisons revealed significant differences between the skin temperature difference in *synchronous* condition in the first 30 seconds and the *synchronous* condition in the third (last) minute ($p < .001$). All other pairwise comparison were not significant ($p > .05$).

4.3.2 Absolute Skin Temperature. To analyze the absolute skin temperature, we additionally included the factor Hand into the statistical analysis. There was no significant main effect of Environment, $F(1, 23) = .021$, $p = .885$, $\eta_p^2 = .000$, of Synchrony, $F(1, 23) = .0.204$, $p = .655$, $\eta_p^2 = .008$, and of Hand, $F(1, 23) = .347$, $p = .561$, $\eta_p^2 = .014$. However, we found a significant main effect of Time on the absolute skin temperature, $F(5, 115) = 27.835$, $p < .001$, $\eta_p^2 = .547$. There was also an interaction effect of Environment × Time, $F(5, 115) = 2.666$, $p = .025$, $\eta_p^2 = .103$. We also found an interaction effect of Synchrony × Hand × Time, $F(5, 115) = 4.829$, $p < .001$, $\eta_p^2 = .173$. Other interaction effects were not significant (all $p > .05$).

4.3.3 Correlation Analysis of the Proprioceptive Drift, the Skin Temperature Difference, and the RHI Questionnaire. We performed a Pearson's correlation analysis of all measures to test whether there is a relationship between the propriceptive drift and the skin temperature, as well as the RHI questionnaire and the skin temperature in the last minute (the third minute) in the *synchronous* conditions. However, we did not find a significant relationship between the measures (all $p > .05$).

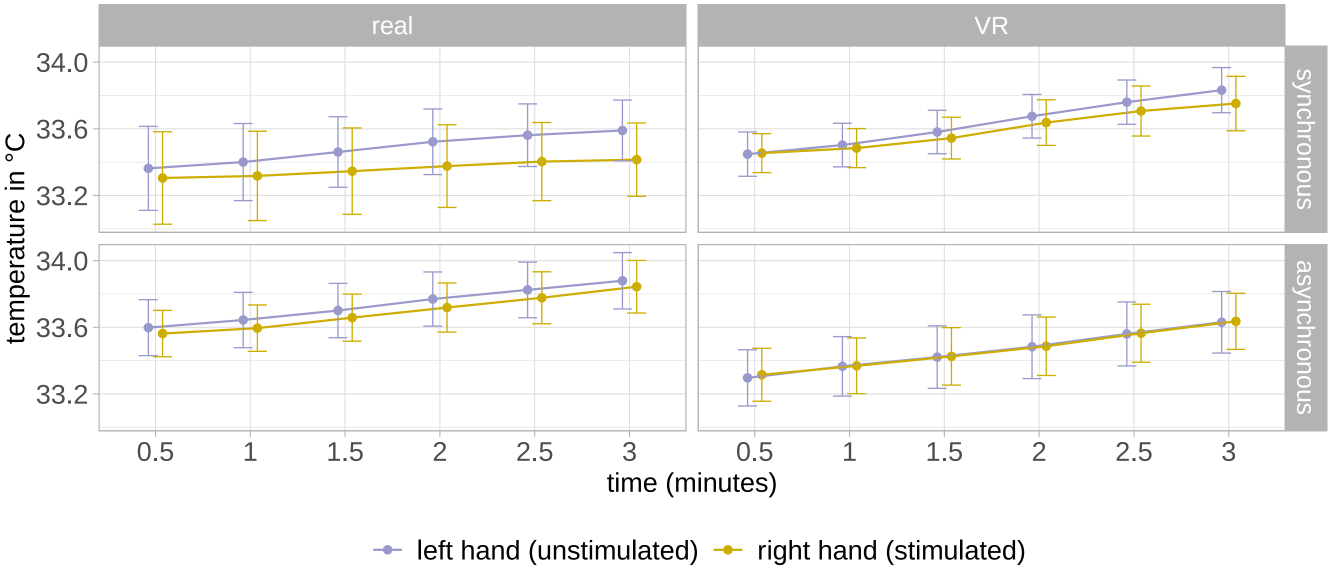

Figure 4: Average temperature per 30 seconds during the RHI in the real world and in VR for synchronous and asynchronous stroking for the left (unstimulated) and right hand (stimulated), respectively. The error bars show the standard error.

5 DISCUSSION

As predicted for both environments, participants had a higher proprioceptive drift during synchronous stroking compared to asynchronous stroking. In VR, the proprioceptive drift was generally higher compared to the real world. As indicated by questionnaire ratings, we found that the participants experienced a stronger RHI during synchronous stroking in both environments.

Our results also revealed that the RHI affected the skin temperature of the own hands. Even if the skin temperature of both hands increased in all conditions, the interaction between SYNCHRONY and TIME indicates that skin temperature difference between right (stimulated) and left (unstimulated) hand increasingly diverge from each other over time due to synchronous stroking (see Figure 3). Hence, there was a lower increase in skin temperature of the stimulated hand during synchronous stroking compared to the increase in skin temperature of the unstimulated hand.

5.1 Physical RHI vs Virtual RHI

We found systematic effects of the RHI performed in the real world and in VR on the proprioceptive drift and the questionnaire ratings. In line with findings from RHI experiments (e.g., [14, 72, 78]), we found a significant higher proprioceptive drift as well as significant higher scores for each dimension of the RHI questionnaire during synchronous stroking compared to asynchronous stroking. However, the proprioceptive drift was generally higher in the RHI conducted in VR compared to the real world.

This is not necessarily an implicit indicator for a higher degree of ownership of the virtual rubber hand in VR. Instead, other factors such as a reduced field of view due to the HMD or a different depth perception in VR could be responsible for such effects [25, 76]. This assumption may be supported by the fact that we could not find significant differences between the effects of both environments on the ratings of the RHI questionnaire. We also did not find any correlation between the perceived embodiment assessed by questionnaire ratings and the proprioceptive drift. This is not surprising as previous investigations found that both measures are not necessarily related to each other due to different underlying mechanisms [53, 74].

When being immersed in VR, not only is the user's hand "replaced" by the virtual rubber hand but the entire body by the virtual body. In other words, in VR the participants did not only experience a limb ownership illusion of the rubber hand but also a full-body ownership illusion of the virtual body. This is in line with Llobera et al. [42], who postulated that when participants enter the VR and perceive a VE from a first-person perspective, the virtual body substitutes the entire real body. Even if we covered the real and virtual body by a hairdressing cape to minimize all identity cues to ensure a high concordance between the real world and VR, small deviations between the own body and virtual self can activate the illusion of embodiment. As we asked about the distance between the real hand and the virtual rubber hand to assess the proprioceptive drift, the position of the real hand, which is a part of the virtual body in VR, can already be misperceived resulting in a higher proprioceptive drift. Future studies should investigate whether multisensory asynchrony, e.g., caused by latency, breaks the illusion on full-body level or only on limb ownership.

For the proprioceptive drift and the ratings of the RHI questionnaire, we could not find an interaction effect of the environment in which the RHI was performed and the synchrony of stroking. However, this does not automatically confirm that the difference in proprioceptive drift and the dimensions of the RHI questionnaire between the *synchronous* condition and the *asynchronous* condition is comparable between environments. The calculated Bayes factors, however, showed anectodal to moderate evidence ($BF_{01} >= 2.162$ and $BF_{01} <= 4.589$) that the data is more likely under the null hypothesis postulating identical RHI effects on the proprioceptive drift and the dimensions of the RHI questionnaire. Hence, our findings suggest that VR technology can be leveraged to create RHIs and increase our understanding of embodying virtual avatars.

5.2 Effects on Skin Temperature

To explain the effects on skin temperature caused by the RHI, we refer to Moseley et al. [47] who revealed that the RHI causes a decrease in skin temperature of the own hand. Notably, the skin temperature of other body parts were unaffected, i.e., the other hand and the feet did not cool. This suggests that the effects depended on the illusion of ownership of the rubber hand.

Moseley et al. [46] introduced the concept of the cortical body matrix to explain the effects of bodily illusions. When the real and the rubber hand are stroked synchronously, the neural areas associated with the space occupied by the rubber hand increase their activity starting to incorporate it into the own body schema, which in turn results in the sensation of the rubber hand being a part of the actual body. On the contrary, the neural areas associated with the space around the real hand decrease their activity, which in turn decreases the extent to which the real hand is "owned" and eventually, results in reduced homeostatic controls, e.g., thermoregulation.

As parts of the cortical body matrix has connections with parts in the brain that regulate autonomic functions, the authors assume that the blood flow to the "disowned" hand is reduced causing a drop in skin temperature. These explanations are in line with Barnsley et al. [5], who showed that participants had an increased histamine reactivity in the stimulated hand during the RHI. As an elevated histamine reactivity is associated with a decreased response of the immune system resulting in a reduced metabolism of histamine, the authors concluded that the stimulated hand during the RHI is treated as when it has been "rejected" [5].

In contrast to Moseley et al. [47], however, it is important to note that we did not induce a cooling of the stimulated hand in a sense that the skin temperature at the end was lower than at the beginning of the RHI. Instead, we found a constant increase in skin temperature of both hands regardless of the vividness of the experienced RHI (see Figure 4). This seemed to be the "normal" physiological response in our experiment. However, our results show that the temperature of the stimulated and unstimulated hand increasingly diverge across time during synchronous stroking (see Figure 3 and 4). During asynchronous stroking, such effects did not occur. We therefore assume that RHI decreased the skin temperature of the stimulated hand in a sense that it attenuated the "normal" increase in skin temperature that occurred in this situation under those circumstances. Although our laboratory is temperature-controlled, the environmental temperature directly around and within the experimental area could also possibly increase affecting the participants' skin temperature. Furthermore, we cannot dismiss thermal reactions caused by social contact through the touch of the experimenter [10, 22, 54].

As we could not find a correlation between the skin temperature differences and the ratings of the RHI questionnaire as well as the proprioceptive drift, we cannot conclude that the embodiment of the physical or virtual rubber hand was responsible for a decreased temperature of the stimulated hand. In accordance to Folegatti et al. [16], we therefore cannot dismiss that changes in skin temperature were caused by the perceptual conflict that is created during the RHI, i.e. the mismatch between the felt and seen tactile cues [16].

5.3 Implications and Future Work

Due to our findings, we argue that the RHI can be transferred into VR resulting in similar and comparable effects. As VR serves an extended design space, it is possible to produce experiences that are hardly feasible or impossible to create in the real world. Virtual rubber hands, for example, with a reduced amount of fingers [33, 59], with a burning skin [12], or with a supernatural length [31] can be easily designed in a VE allowing a high degree of control over the experimental variables.

Regarding the effects on the skin temperature, it is important to consider this phenomenon when creating embodied VR experiences. Researchers have to know how limb ownership illusions influence the basal skin temperature as such effects may confound physiological measurements, e.g., the skin conductance response [43]. As the human body's temperature regulation processes involve thermal signals from the skin [55], the activity of sweat glands therefore partially depends on the skin temperature [43].

Such effects may also be explained within the theoretical framework of the Proteus effect that describes behavioral, perceptual, and attitudinal changes caused by an avatar's stereotypical visual appearance [32, 34, 37, 79]. The embodiment of a virtual hand whose rubbery appearance is associated with artificiality and inanimateness may potentially could cause participants to move their hand less in terms of micromovements than they would with a vital and lifelike hand resulting in a drop in skin temperature. This can be addressed in future work.

6 CONCLUSION

In this paper, we compared the RHI in the real world with a RHI in VR. We conducted a study with 24 participants who experienced the RHI in the real world and in VR. The proprioceptive drift as well as the ratings of the RHI questionnaire were higher during synchronous stroking compared to asynchronous stroking in both environments. Equivalent tests using the Bayes factor revealed that the differences between the effects on the proprioceptive drift and the ratings of the RHI questionnaire caused by synchronous stroking and asynchronous stroking were more likely identical for both environments. These findings imply that the RHI causes similar and comparable effects in both environments. Hence, this work validates that the RHI can be leveraged in VR to increase our understanding of BOIs and the virtual embodiment of avatars.

We also found that the RHI affected the skin temperature of the real hands. Even if the skin temperature of both hands increased, the skin temperature of the right hand (stimulated) and the left hand (unstimulated) increasingly diverge from each other across time during synchronous stroking. These insights extend our knowledge about the consequences of limb ownership illusions for the own body and illustrate the psychophysiological impact of embodying virtual limbs on users.

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