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Self-Controlled Continuous Brushing with Vibrotactile Feedback Enhances the Rubber Hand Illusion in Virtual Reality

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***Abstract*—Feeling ownership of a virtual body in Virtual Reality (VR) enhances the immersion and quality of user experience. Inducing body ownership in VR is mainly based on the Rubber Hand Illusion (RHI) experiment, where watching a rubber hand being stroked while the natural hidden hand is synchronously stroked, induces an illusion of ownership for the rubber hand. Tactile feedback plays a vital role in inducing the RHI in VR. While previous research showed that vibrotactile feedback significantly improves the quality of the illusion, it remains unclear what type of brushing is more effective. In this study, we consider two brushing parameters: (1) self-brushing versus brushing by others and (2) discrete versus continuous brushing. We developed a VR simulation and a haptic sleeve to simulate the RHI through five experimental conditions: control (without haptics), self-discrete, self-continuous, other-discrete, and other-continuous. A total of 85 participants, divided across the 5 experimental conditions, took part in the experiment. The quality of the RHI was assessed using two standard tests, namely proprioceptive drift and an ownership illusion questionnaire. The results indicated that while the control condition (no brushing) showed no significant improvement, all types of brushing resulted in a significant increase in the quality of the illusion. Furthermore, across the four brushing conditions, the self-continuous condition showed a significant increase in the quality of the illusion as compared to the control condition.**

***Index Terms*—Rubber Hand Illusion, Virtual Reality, VR, Haptic Feedback, Sense of Ownership, Self-Touch, Continuous Brushing, Discrete Brushing, Embodiment**

I. Introduction

A human perceives their body as a coherent blend of sensory expressions (such as vision, touch, and proprioception). Body illusions refer to psychological phenomena in which the perception of one's own body deviates from the physical one in terms of size, location, shape, etc. [1]. Body illusions support several applications, including improved quality of immersion and user experience in Virtual Reality (VR) [2], brain-computer interaction [3], limb rehabilitation [2], and human cognition and self consciousness [4]. The Rubber Hand Illusion (RHI), a widely utilized phenomenon for body ownership [5], is an multisensory illusion where an inanimate rubber limb is perceived as being real through the synchronous application of visual and tactile stimuli. During the experiment, the experimenter applies brushstrokes to the hidden real hand of the participant, and simultaneously, to a rubber hand next to it, with each brushstroke lasting 1-second intervals [6].

VR allows users to experience a sense of body ownership through digital representations of the human body and create embodied experiences [7]. Early studies to virtualize the RHI used video projectors [8], where the degree of immersion was severely limited by the technology of that time. Nowadays, with the advent of VR head-mounted displays, there are new opportunities to push the boundaries of immersion, and replicate the RHI in a controlled environment. Multiple studies, such as Yuan et al. [9] and Kocur et al. [10], suggest that VR Headsets enhance the body ownership and agency in virtual RHI. The main difference between RHI in VR and in the real world is that proprioceptive drift (the shift in the perceived position of a person's real limb) is generally larger in VR, possibly because of the reduced field of view or differences in depth perception. Studies have shown that to best induce the RHI, the VR simulation (1) must be in first-person perspective, (2) must have profoundly realistic skin tone, texture, and clothing, and (3) offers additional sensory feedback, such as touch or proprioception [11].

More recent research investigated the effectiveness of sensory feedback, in the form of vibration, vibrotactile, kinesthetic, or proprioception, to improve the quality of the RHI. Cheng et al. [3] demonstrated that different experimental conditions affect body ownership to different degrees. The study examined active (participants freely moving their own hand and thus providing proprioception) and passive (experimenter placing a paper under the participant's hand and dragging the paper) movements and reported that proprioceptive feedback significantly improved the illusion. Many other parameters may influence the quality of the illusion [12]. For instance, previous research showed conflicting results for the time it takes for the illusion to emerge (ranging from a few seconds to minutes). Other factors include the brushed body part, brushing speed, and the modalities involved (such as visual, vibrotactile, or kinesthetic).

One important aspect that provides critical insights into the mechanisms of body ownership is the distinction between self-touch (active) and touch by others (passive). Self-touch refers to the condition where the participant actively performs the brushing on their own hand, while touch by others refers to brushing applied by an external agent. Research has shown that in real-world (non-virtual) experiments, both self and touch by others activate the RHI, suggesting different combinations of sensory input lead to an experience of body ownership [13]. There have been conflicting findings on whether self-touch or touch by others results in better body ownership. Studies such as Braun et al. [14] suggested that body ownership illusion is stronger in self-touch conditions. However, in other studies, such as Kilteni et al. [15] participants reported that self-touch induced weaker body ownership due to sensory attenuation—the brain's ability to reduce the intensity of self-generated sensations.

Previous research considered incorporating automated haptic feedback systems in the RHI in VR. Given the bulkiness and inefficiency of kinesthetic haptic devices, most literature considered mechanotactile, vibrotactile, electrotactile and midair haptic stimulation [16]. Study [17] demonstrated that RHI can be activated in active, dynamic, and multisensory virtual environments. A subsequent study considered combination of modality matched, modality mismatched, synchronous and asynchronous stimulation [18]. Related work on similar haptic illusions in VR includes research on the Cutaneous Rabbit Illusion, investigating how visual locomotion and tactile stimuli duration affect emotional dimensions [19], [20], providing valuable insights into haptic perception in virtual environments. Results indicated that vibrotactile sensory substitution can be used to induce the illusion when synchronous but modality conflicting visuo-tactile stimulation is delivered. A recent study examined three modalities for tactile stimulation, electricity, pressure, and vibration [16]. The study concluded that electrical and vibration stimulation induced a stronger illusion than pressure. VR enables managing environments that are hard to control in the real world as well as better observe emotional responses [21]. On the other hand, it has also been shown that the time required to perform a motor task in VR is very different from that in the real world [22]. Therefore, the way in which RHI can be generated in VR may not be the same as in the real world.

The aim of this study is to investigate two research questions, namely (1) whether immersive VR and vibrotactile feedback can reliably activate the RHI, and (2) if so, which specific type of brushing (self-touch vs. touch by others and discrete vs. continuous) is the most effective. A VR simulation and haptic sleeve are developed to address these questions by dividing participants into five experimental groups: a control condition (no brushing), self-discrete, self-continuous, other-discrete, and other-continuous.

II. Methodology

A. Participants

A total of 85 participants were enrolled in this study. The protocol was approved by the Institutional Review Board

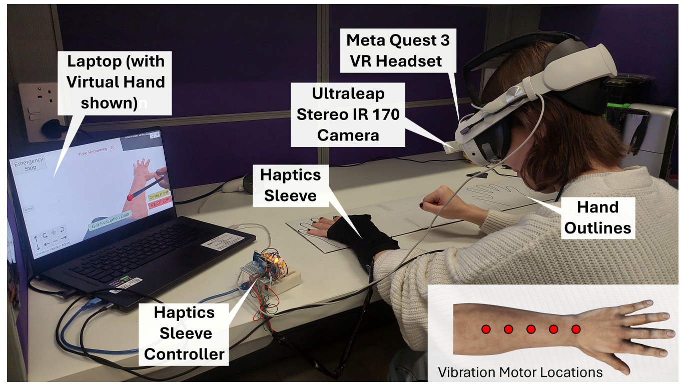


Fig. 1: Experimental Setup showing the virtual hand in the laptop, in synchronization with the real hand brushing movement)

(IRB Number, HRPP-2022-99). All participants were at least 18 years old and gave their informed consent. Of the 85 participants, 73 were between the ages of 18 and 25 years. The gender distribution is 53 males and 32 females. Only 15 of the participants reported prior knowledge of the RHI. Participants were also asked to rate their familiarity with VR, from 1 (new to VR) to 5 (familiar with VR). Participants' average VR familiarity score was 2.75 (on a 5-point Likert scale) with a standard deviation of 1.17.

B. Experiment Setup

As shown in Figure 1, the experiment comprises the following components: (1) a Unity-based VR simulation, (2) a Meta Quest 3 VR headset, (3) a gaming laptop running the simulation through Meta Quest Link for real-time rendering of the virtual scenario, (4) an Ultraleap Stereo IR 170 camera to supplement the default hand tracking for enhanced fidelity, (5) a custom Haptics Sleeve with five evenly spaced vibration motors to provide vibrotactile feedback on the participant's lower arm, (6) a Haptics Sleeve Controller (using an Arduino UNO R3 board with DRV2605L drivers) to handle the vibration signals, and (7) hand outline on the table to control the position of the participant's arms on the desk.

The data flow block diagram for all the components mentioned above is visualized in Figure 2. The Ultraleap Stereo IR 170 camera (attached to the VR headset) captures the hand tracking data and sends it to the RHI VR simulation. The VR simulation renders visual feedback using the Meta Quest 3 VR headset. Simultaneously, the RHI simulation sends commands to the sleeve controller to activate the corresponding motor(s) and provide a synchronized vibrotactile experience. The sleeve controller generates and sends the actuation signals to the vibration motors.

C. VR Simulation Development

As suggested by Maselli et al. [11], a VR simulation was developed using Unity 3D software in first-person perspective with realistic skin texture and vibrotactile feedback to reliably induce the RHI. The duration of the brushing is kept at 45

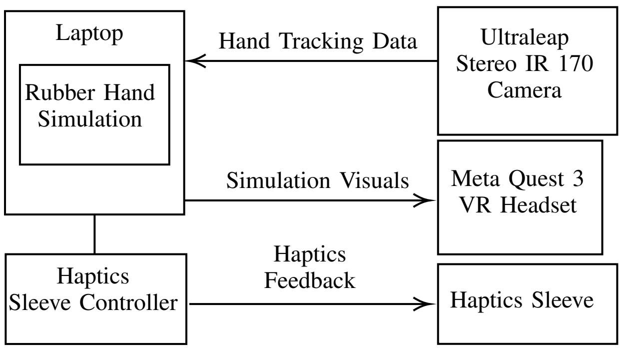


Fig. 2: VR Simulation Block Diagram

seconds across the conditions based on previous literature [12]. The left virtual hand is the hand being brushed in all experimental conditions. Throughout all the experiment conditions, the brush speed is kept constant to ensure consistency (2.5 cm/second). During the self-touch conditions, the speed is controlled through a red indicator (a simple visual guide appearing as a small dot) that participants were instructed to follow with the brush to maintain the desired speed. This indicator was designed to be minimally intrusive and was present in both self-touch conditions (discrete and continuous) to ensure experimental consistency, thus any difference between these conditions cannot be attributed to the presence of the indicator itself.

For the experiment, participants did not hold a physical brush but interacted with the virtual brush through hand tracking. While having a physical object might potentially amplify the illusion through additional proprioceptive cues, we chose to isolate the effects of visual and vibrotactile feedback without introducing potential confounding variables from physical objects. The custom Haptics Sleeve was programmed to induce continuous vibrotactile stimulation using the funneling illusion phenomenon [23], a technique to reduce the number of tactile actuators on the body, while maintaining the illusion of a smooth, continuous, vibration sensation. The vibration intensity of the motors is dynamically varied based on the Euclidean distance between the corresponding motor and the brush in the virtual environment, in real-time. The dynamic vibration intensity of the n^{th} motor, I_n, is calculated by a custom linear mathematical model shown in Equation 1.

$$I_n(x,y,z) = M_n \tfrac{255}{d}\left(d - \sqrt{(x-x_n)^2+(y-y_n)^2+(z-z_n)^2}\right) \quad (1)$$

Where: I_n is the motor vibration intensity. M_n is a multiplier of motor intensity per motor. d is the distance between any two adjacent motors. (x_n, y_n, z_n) is motor n's position on the sleeve. (x, y, z) is the brush's position in virtual space.

The output intensity signal from this model is fed into the Haptics Sleeve controller as pulse width modulation (PWM) signal. As the brush gets closer to a particular motor, the corresponding motor vibrates more strongly, creating a continuous vibrotactile perception.

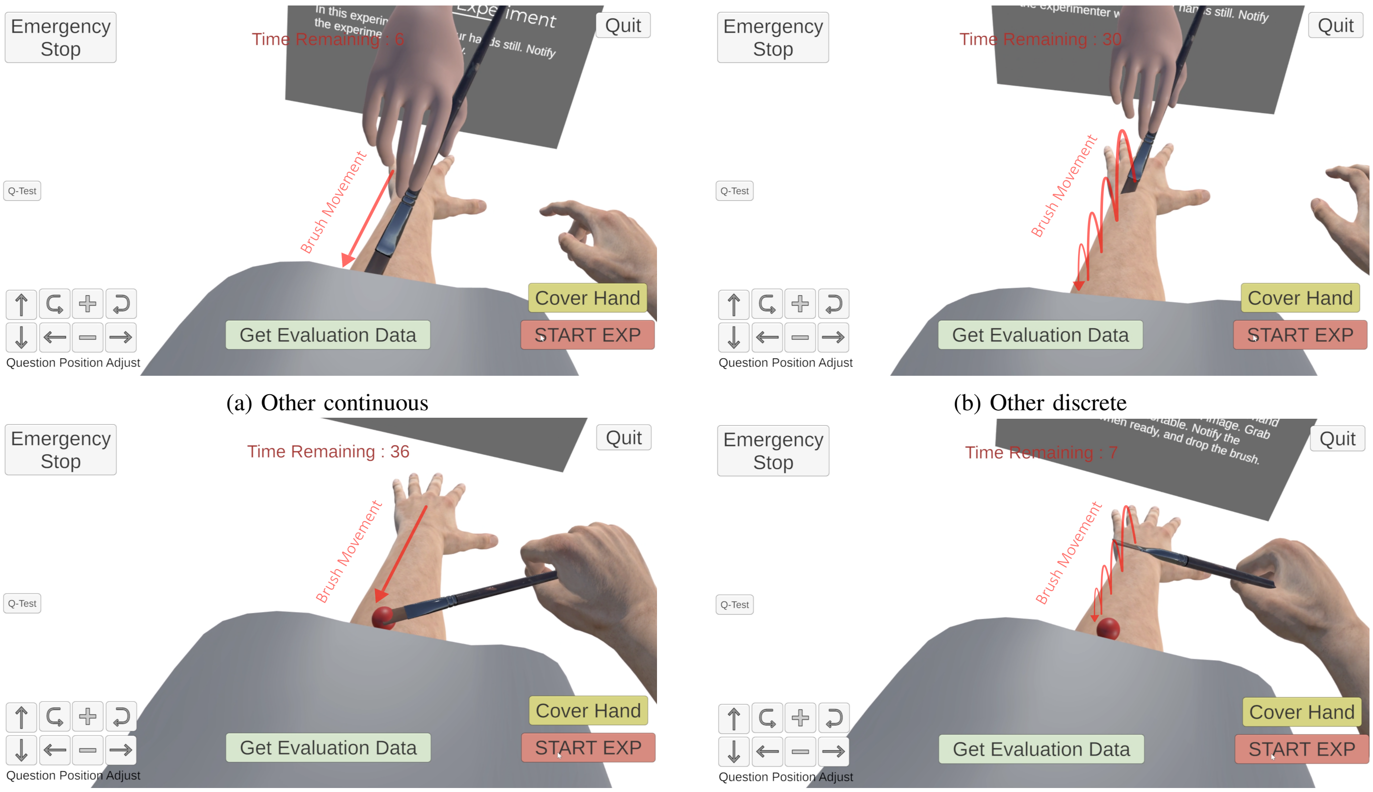
D. Experimental Protocol

The experiment was carried out in an enclosed space, free from distractions. At the beginning of the experiment, the researcher explained the experimental protocol and task. The participant was then asked to sign an Informed Consent Form and complete a demographics questionnaire for their age range, gender, familiarity with VR, and prior knowledge about the RHI. Afterward, the participant is assigned to one of the five groups:

- **Control:** In this condition, participants observe their virtual hand without vibrotactile feedback or brushing. This condition serves as a baseline to compare the effects of other conditions, and to isolate the effects of different types of vibrotactile feedback and brushing on the RHI.
- **Other continuous** As shown in Figure 3a, a hand avatar (controlled through the software) uses the brush to perform smooth, continuous brushing strokes on the participant's virtual hand, while the participant remains passive and observes the action.
- **Other discrete** As shown in Figure 3b, a hand avatar (controlled through the software) uses the virtual brush to tap discrete points on the participant's virtual hand. Participants remain passive and observe the action, without actively controlling the brush.
- **Self continuous:** As shown in Figure 3c, participants use a virtual brush to make smooth, continuous brushing strokes on their own virtual hand. The brushing motion is fluid and uninterrupted, providing a prolonged tactile experience.
- **Self discrete:** As shown in Figure 3d, participants actively use a virtual brush to tap discrete points on their own virtual hand, guided by a red indicator displayed in the virtual environment where they should tap.

Participants were given a training session to familiarize themselves with the experimental setup (particularly for the self-brushing conditions). In the practice session, the participant is provided with a virtual brush to become familiar with the brushing technique in VR.

The main experiment consisted of (1) measuring the proprioceptive drift error, (2) brushing for 45 seconds by instruction, (3) measuring the proprioceptive drift error after the brushing, and (4) completing a post-experiment questionnaire to evaluate RHI. The protocol for measuring the proprioceptive drift error was as follows: the left virtual hand is covered with a virtual planar board, and the participant was instructed to place a chess piece on the hand landmarks (thumb tip, middle fingertip, pinky fingertip, wrist, and forearm) based on their perceived location. The distance between the location of the virtual hand landmark, and the chess piece is recorded as the proprioceptive drift error. The average error



(a) Other continuous (b) Other discrete (c) Self continuous (d) Self discrete

Fig. 3: Screenshots of the VR simulation, showing different conditions of the experiment (Red arrow indicates the trajectory of brush motion).

for the five hand landmarks was calculated. Participants then experienced the brushing with the corresponding vibrotactile feedback assigned to their group. Finally, the participant, while still in the VR environment, completed the Post-Experiment Questionnaire (a total of 10 questions, shown in Appendix A) to evaluate the quality of the illusion [24]. Note that the control group was instructed to wait 45 seconds without interaction until further notice.

E. Data Analysis

To evaluate proprioceptive drift error, we examined the difference in proprioceptive drift before and after the brushing task. We averaged the proprioceptive drift errors of the five locations to investigate whether there was a significant improvement in the RHI due to different types of brushing tasks. As for the questionnaire analysis, the scores of the 10 responses were averaged for each participant. Participants with an average questionnaire score (across all 10 questions) outside the range of mean ± 2 SD were removed as outliers. This criterion was applied to identify participants who may have misunderstood the instructions, experienced technical issues with the equipment, or showed extremely atypical responses to the RHI. This approach is consistent with standard practices in perceptual research to ensure data quality while maintaining a representative sample.

Statistical analysis for whether the actual illusion occurred in each group was conducted using the Wilcoxon signed-rank test and the Benjamini and Hochberg false discovery rate. Significant differences between the groups were also tested using the Kruskal-Wallis test with Bonferroni p-value correction.

III. Results

In examining whether the RHI was activated in each group, the RHI score was compared before and after the brushing task. Table I shows the evaluation of the quality of RHI participants had. In the control group, there was no significant improvement in the RHI score (Wilcoxon signed-rank test, Benjamini and Hochberg's false discovery rate, $p > 0.05$).

TABLE I: Illusion evaluation from the post-experiment questionnaire. Wilcoxon signed-rank test, Benjamini and Hochberg's false discovery rate.

	Mean	SD	*p*-value	
Control	0.5471	1.3436	0.0975	NS
Other continuous	0.8824	1.2310	0.0161	*
Other discrete	1.5938	0.9441	0.0003	***
Self continuous	1.8533	0.8847	0.0003	***
Self discrete	1.5250	1.0010	0.0007	***

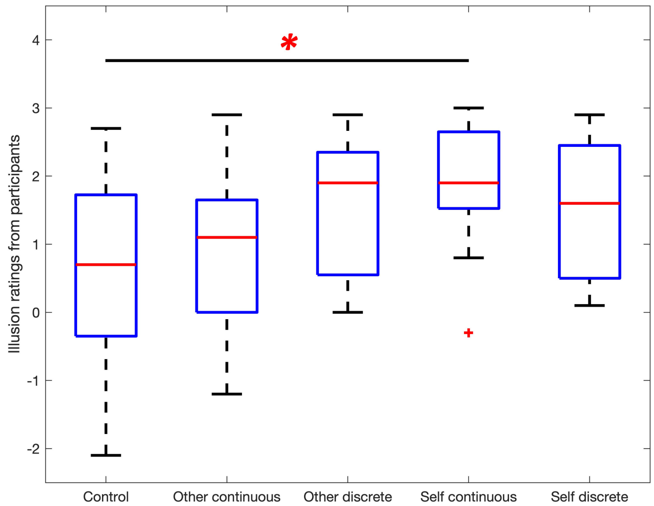


Fig. 4: Differences in illusion from the post-experiment questionnaire between five groups. Kruskal–Wallis test, Bonferroni correction, * $p < 0.05$

This implies that merely watching the virtual hand in VR did not activate the RHI. However, a significant improvement in the RHI was found in the other-continuous (Wilcoxon signed-rank test, Benjamini and Hochberg's false discovery rate, $p < 0.05$). Furthermore, more significant improvement in the RHI was found in the discrete-other, discrete-continuous, and self-continuous conditions (Wilcoxon signed-rank test, Benjamini and Hochberg's false discovery rate, $p < 0.001$). Therefore, it can be confirmed that, except for the control condition, the RHI is activated in all four conditions (discrete/continuous and self/other brushing).

Whether there was a significant difference in the RHI between each group was also tested. As shown in Figure 4, a significant difference between the control group and the self-continuous group was found (Kruskal-Wallis test with Bonferroni correction, $p < 0.05$). It can therefore be concluded that, when creating the RHI in VR, self-induced and continuous brushing seems the most effective to activate the illusion.

For the proprioceptive drift error, no significant differences were observed across the experimental conditions. There was also no significant effect of gender or VR familiarity on the RHI experience.

IV. Discussion

Our results show that self-continuous brushing significantly enhances the RHI in VR. This aligns with the Bayesian causal inference model explanation in literature [6], where the brain prioritizes the temporally synchronized, spatially congruent multi-sensory inputs. The self-continuous condition provides visuo-tactile coherence for a prolonged duration (relative to discrete brushing conditions), thus enabling the robust integration of motor commands, proprioception and visual feedback, which are the key drivers of body ownership [14]. The implementation of the funneling illusion amplified this effect by simulating a more natural brushing sensation. In contrast, discrete brushing introduced temporal gaps and reduced sensory evidence. The other-touch conditions lacked agency, weakening the closed-loop feedback critical for embodiment.

Our results resolve contradictions in the earlier RHI studies. While researchers such as Kilteni et al. [15] reported attenuated ownership during self-touch due to sensory suppression, our study counteracted this through immersive VR and continuous vibrotactile feedback. Our study supports Cheng et al.'s [3] finding that active movement, with vibrotactile addition maximizes embodiment in VR.

Evaluating the quality of the RHI is commonly conducted through 2 main methods: (1) proprioceptive drift by means of a post-experiment pointing task and (2) subjective data collection in the form of questionnaires. Although proprioceptive drift measurement provides a quantitative assessment, multiple studies suggested that there is no causal link between proprioceptive drift and the RHI [25], [26]. Regarding the questionnaires, it was found that participants reported a stronger RHI when asked to focus on their subjective feelings (where they think their hand seems to be) compared to their objective beliefs (where they think their hand physically is). From our results, proprioceptive drift measurements seem to be unreliable due to their disputed link to ownership [25] in this experiment.The establishment that subjective questionnaires show better capture of the RHI experience in this study.

Our findings have immediate applications in VR rehabilitation and training. For example, by successfully inducing body ownership for stroke patients, self-controlled continuous brushing could enhance motor recovery for post-stroke patients [27]. Similarly, self-controlled continuous brushing paradigm can be applied to motor imagery brain-computer interfaces (BCIs) to improve neuroprosthetic control [28]. Finally, our results suggest that self-controlled continuous brushing can improve the quality of immersion in gaming and virtual and social interactions.

While our results are statistically significant, the sample size (17 participants per group) limits the generalizability of the findings. Although this sample size exceeds many comparable studies in haptics research, future work should aim to validate these findings with larger and more diverse populations, particularly considering the medium to large effect sizes observed in our results. Moreover, even though the 45-second exposure is the standard for RHI research [12], our study may not reflect embodiment in long-term VR exposure. Future studies should investigate the temporal dynamics of the illusion, exploring whether the observed effects persist, strengthen, or diminish during extended VR interaction sessions that more closely resemble practical applications. This is particularly important for applications like rehabilitation, where sessions typically last 30 minutes or more. For future studies, recruiting larger and more diverse cohorts across different age groups, VR experience levels, and cultural backgrounds is essential. Our current sample primarily consisted of young adults (18-25 years) with moderate VR familiarity (average score of 2.75 on a 5-point scale), limiting generalizability to populations such as older adults or VR novices. Additionally, incorporating objective neurophysiological metrics (e.g., skin conductance response to threat, electroencephalography, or functional magnetic resonance imaging) could address potential biases inherent in self-report measures and provide insights into the underlying neural mechanisms associated with different types of brushing. These enhancements are particularly relevant for rehabilitation and therapeutic applications, where target users often include older adults with limited technology experience and potentially different sensory processing characteristics.

V. Conclusion

This study demonstrated that the RHI can be successfully activated with a virtual brushing task using VR and vibrotactile feedback regardless of the type of brushing (self brushing or by others, continuous or discrete). Furthermore, self-induced continuous brushing provided a significant improvement of the RHI as compared to the control condition (no brushing). By demonstrating the critical interplay between agency, stimulation continuity, and closed-loop feedback, our study provides a blueprint for designing VR haptic systems that maximize body embodiment.

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Appendix

A. Questionnaire

1) *It seems I was looking directly at my own hand, rather than at a virtual hand.*
2) *It seems the virtual hand began to resemble my real hand.*
3) *It seems the virtual hand belonged to me.*
4) *It seems the virtual hand was my hand.*
5) *It seems the virtual hand was part of my body.*
6) *It seems my hand was in the location where the virtual hand was.*
7) *It seems the virtual hand was in the location where my hand was.*
8) *It seems the touch I felt was caused by the paintbrush touching the virtual hand.*
9) *It seems I could have moved the virtual hand if I had wanted.*
10) *It seems I was in control of the virtual hand.*

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