A Virtual Reality Application of the Rubber Hand Illusion Induced by Ultrasonic Mid-Air Haptic Stimulation

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ABSTRACT

Ultrasonic mid-air haptic technologies, which provide haptic feedback through airwaves produced using ultrasound, could be employed to investigate the sense of body ownership and immersion in virtual reality (VR) by inducing the virtual hand illusion (VHI). Ultrasonic mid-air haptic perception has solely been investigated for glabrous (hairless) skin, which has higher tactile sensitivity than hairy skin. In contrast, the VHI paradigm typically targets hairy skin without comparisons to glabrous skin. The aim of this paper was to investigate illusory body ownership, the applicability of ultrasonic mid-air haptics, and perceived immersion in VR using the VHI. Fifty participants viewed a virtual hand being stroked by a feather synchronously and asynchronously with the ultrasonic stimulation applied to the glabrous skin on the palmar surface and the hairy skin on the dorsal surface of their hands. Questionnaire responses revealed that synchronous stimulation induced a stronger VHI than asynchronous stimulation. In synchronous conditions, the VHI was stronger for palmar stimulation than dorsal stimulation. The ultrasonic stimulation was also perceived as more intense on the palmar surface compared to the dorsal surface. Perceived immersion was not related to illusory body ownership per se but was enhanced by the provision of synchronous stimulation.

CCS CONCEPTS

•Human-centered computing → Human computer interaction (HCI) → *Empirical studies in HCI* •Human-centered computing → Human computer interaction (HCI) → Interaction paradigms → *Virtual reality*

•Human-centered computing → Human computer interaction (HCI) → Interaction devices → *Haptic devices*

KEYWORDS

Virtual hand illusion, body ownership, ultrasonic mid-air haptics, Ultrahaptics, skin type, immersion.

1 Introduction

We know that some body parts like our brain belong to us, but other body parts such as our hands and the body as a whole have a special perceptual status – we not only know they belong to us, but we also *feel* it [19]. The sense of body ownership is the experience that one's body and certain body parts belong to oneself and is a component of embodiment, which is the overall experience of having a body [42]. In this paper, unless specified otherwise, the term body ownership will be used in the particular case of hand ownership.

Illusions which reveal that, under specific experimental conditions, external objects can be perceptually attributed to one's body, have become the primary window into body ownership because they help us understand the factors that underpin and modulate this bodily experience [20, 21, 24]. The current paper will focus on the rubber hand illusion (RHI), the most comprehensively investigated body ownership illusion [27, 74]. This section considers the RHI induced in real-life settings before shifting to technologically-mediated RHI implementations employing virtual reality (VR) technologies – the virtual hand illusion (VHI), as well as automated haptic technologies. We then introduce an experiment which induced the VHI employing an Ultrahaptics device, which is a non-invasive haptic technology that provides ultrasonic mid-air haptic feedback, both on the palmar and dorsal sides of participants' hands.

Botvinick and Cohen [8] introduced the RHI by using two paintbrushes to synchronously stroke the participant's occluded left hand and a rubber hand placed in an anatomically plausible and visible position. Through a self-report questionnaire, they found that participants perceived the rubber hand as part of their own body, attributing the tactile stimulation they felt to the rubber hand. Moreover, Botvinick and Cohen [8] employed a behavioural measure later termed proprioceptive drift [90], which involved blindly pointing to one's hand before and after the brushing. There was a significantly larger displacement of the perceived location of the participant's real hand towards the rubber hand after synchronous compared to asynchronous stroking. The magnitude of this spatial displacement was correlated with the questionnaire ratings.

Physiological measures have also been employed to capture the subtle differences in individuals' experience of body ownership. First employed by Armel and Ramachandran [4], skin conductance responses (SCRs) have become widely used as an autonomic RHI metric [53, 64, 78]. SCRs are quantifiable changes in skin conductance resulting from increased sweat gland activity induced by discrete stimuli [9]. In the case of the RHI, these stimuli could be painful movements, knives or hammers that threaten the integrity of an embodied rubber hand and induce SCRs that are similar to the SCRs resulted from threatening one's real hand [57]. This measure is a sensitive index for arousal as it captures responses occurring at an unconscious level which cannot be controlled at will [18]. Therefore, both the subjective questionnaire and objective SCRs can quantify the RHI as converging dimensions of body ownership.

The RHI has also been induced in VR, where individuals experience illusory ownership over virtual bodies and body parts following synchronous visuo-tactile or visuo-motor feedback [e.g., 39, 45, 49, 69, 78, 89, 92, 95]. VR is an ideal tool for investigating body ownership as it allows for highly controlled, flexible and systematic manipulation of a wide range of parameters, whilst also maintaining ecological validity [63]. Ecological validity is achieved by creating contextually rich and naturalistic environments that provide multimodal sensory stimulation and elicit reactions similar to analogous real-life scenarios [41, 46, 62, 63]. As VR facilitates a representative design of a real-world scenario a participant may find themselves in, our study's variables and conclusions will be relevant to the real-world context of the RHI. Moreover, there seems to be a relationship between synchronous visuo-tactile stimulation, illusory body ownership and the degree of VR immersion, which is illustrated in Figure 1. Immersion, an objective indicator of VR efficacy, refers to the quality of VR to seem realistic or believable and sets the boundaries for users' sense of presence or of "being there", which is a subjective index of VR efficacy [77]. It appears that body ownership and immersion share some of their underlying mechanisms [32, 75]. More specifically, the provision of sensorimotor contingencies seems to be a contributing factor to both immersion and body ownership through the VHI [82, 85]. Therefore, body ownership and immersion seem to be interconnected in multiple ways [92].

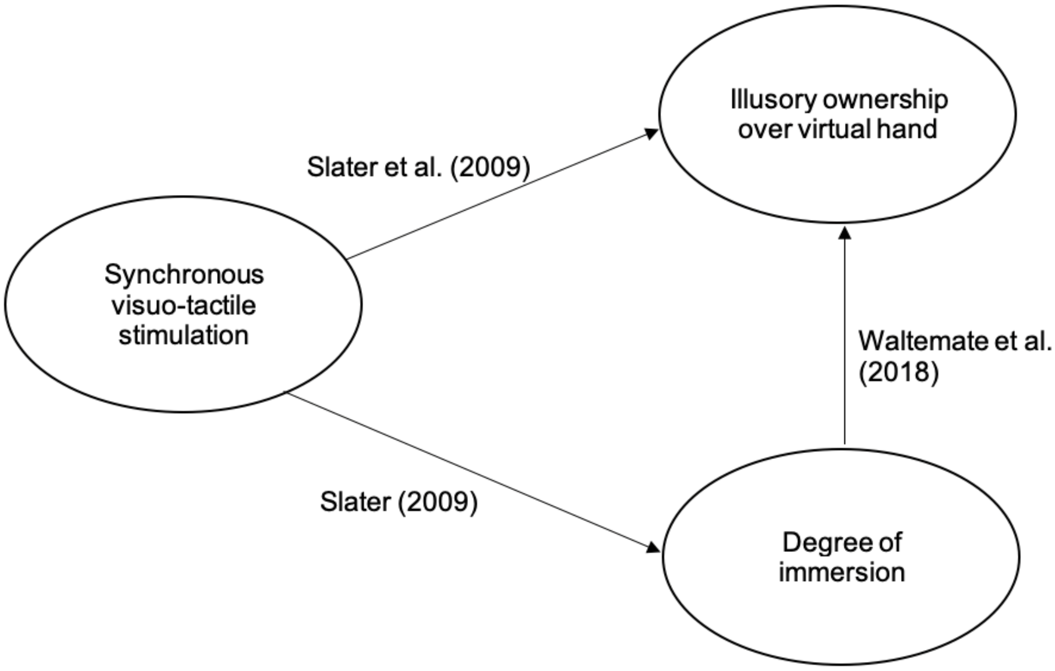

Figure 1. Relationship between synchronous visuo-tactile stimulation, illusory ownership over the virtual hand and the degree of immersion.

While all the aforementioned studies employed contact-based touch, the latest development in the field of automated haptic stimulation, ultrasonic mid-air haptics, has only recently started to be investigated in the VHI context [17, 72]. These technologies can deliver tactile feedback without any physical contact with the devices or actuators [70]. Ultrahaptics systems use acoustic radiation pressures obtained through the projection of focused ultrasound originated from a phased array of ultrasonic transducers directly on individuals' skin, producing a haptic sensation often described as air or breeze [14, 59]. Ultrahaptics can render dynamic patterns which induce the sensation of movement with discernible direction and localisation, which is essential for VHI induction [71, 93]. The real-life RHI has successfully been replicated employing an ultrasonic mid-air haptic device. Horiuchi, Yoshida, Makino and Shinoda [37] used an airborne ultrasound tactile display (AUTD) and an animated projection that moved in synchrony or asynchrony with the ultrasound stimulation on the dorsal side of a rubber hand. They induced ownership over the rubber hand in the synchronous condition as revealed by self-report questionnaires and proprioceptive drift. Mid-air haptic feedback has also been used to induce the VHI [72]. Participants reported increased body ownership over a virtual hand presented from a first-person perspective following synchronous visuo-tactile feedback compared to asynchronous visuo-tactile feedback when one stimulus (i.e., raindrop) was presented at a time. This finding was supported by a proprioceptive drift measure. In a real-life RHI setup, Pittera et al. [72] also tested the effect of stimulus location on RHI intensity and reported that participants experienced a similar intensity of the RHI when their palms and the back of their hands received visuo-tactile stimulation. However, Pittera et al. [72] did not investigate the effect of stimulus location on body ownership in the VHI context and by applying mid-air haptic stimulation, so whether a similar effect is found with these types of stimuli remains unknown.

Investigating this would be particularly interesting considering that the psychophysical research on ultrasonic mid-air haptic technology is still in its infancy. The perceptual thresholds to ultrasonic mid-air stimulation have solely been explored for the glabrous (hairless) skin of the palm, but not the hairy skin found on the dorsal side of the hand. The detection of vibrotactile stimuli seems to be significantly poorer on hairy compared to glabrous skin, both at low and high stimulus frequencies [40, 54]. These sensitivity differences have been partly attributed to differences in the distribution of mechanoreceptors across the arm and hand [17]. More specifically, the Meissner corpuscles, sensitive to low-frequency vibrations below 80 Hz [54], and the Pacinian corpuscles, sensitive to high-frequency vibrations ranging from 50 Hz to ten kHz [36], have both been associated with ultrasonic mid-air stimulation and are predominantly found in glabrous skin [40, 71]. Hence, the tactile sensitivity to the mid-air haptic stimulation might be lower on the dorsal side resulting in higher detection thresholds on the dorsal compared to the palmar surface of the hand. This might result in a less strong VHI when the mid-air haptic stimulation targets the dorsal surface, compared to the palmar surface. This would be particularly interesting as VR potentially acts as a distractor which increases tactile perception thresholds [47]. Investigating these aspects would offer insights into the properties of ultrasonic mid-air haptic stimulation on glabrous and hairy skin and the influence these properties might exert on VHI strength. This is important to explore in order to grasp the anatomical factors that may influence individuals' experiences with different multimodal VR applications that the VHI might be used for.

The current study applies the rubber hand illusion as delivered in virtual reality and without physical contact with a mid-air tactile device to investigate the applicability of combining full visual immersion with the use of ultrasonic mid-air haptic stimulation. In addition, we compared the potential influence of skin sensitivity on VHI strength. We induced the VHI by employing mid-air haptic stimulation targeting both the glabrous skin on the palmar surface and the hairy skin on the dorsal surface of the hand, as revealed by both subjective and physiological measures. Moreover, the relationship between the synchrony of visuo-tactile feedback, illusory body ownership and perceived VR immersion was explored. First, we hypothesized that the subjective and objective VHI experience will be stronger when the visual and mid-air haptic stimulation are synchronous compared to when the visual and mid-air haptic stimulation are asynchronous, as suggested by previous VHI studies [49, 75]. Secondly, the perceived tactile intensity of the mid-air haptic stimulation will be higher on the palmar compared to the dorsal side of the hand. Thirdly, we predicted that the perceived VR immersion will be stronger when the visuo-tactile stimulation is synchronous than when the visuo-tactile stimulation is asynchronous.

2 Materials and Methods

2.1 Participants

Fifty participants (five males, 45 females) were recruited through opportunity sampling, mainly from an academic mailing list. Their ages ranged from 18 to 30 years (M = 20.50, SD = 2.47). Four participants were left-handed and 46 were right-handed according to the Edinburgh-Waterloo Handedness Questionnaire (E-WHQ) [28]. All participants but one were students. All participants had normal or corrected-to-normal vision with contacts and no epilepsy or history of seizures. Participants received £10 as remuneration upon completion of the study.

2.2 Materials and Apparatus

A virtual classroom, created with the Unity3D game engine, was used in this study. A rigged right-hand model was included in the virtual environment, which was seen from a first-person perspective. The process of rigging allowed individual finger movements to be captured by the camera mounted on the ultrasonic transducer to facilitate hand tracking - and applied to the virtual hand, which was animated as the participant moved her/his hand and individual fingers [6]. We selected a 3D hand model such that the virtual hand looked gender-neutral and resembled a real white hand as closely as possible in terms of shape and skin texture. The virtual hand was attached to a wrist and forearm, as it was suggested that VHI induction is highly dependent on the connectivity between the hand and the rest of the virtual body [66].

There were two virtual objects used to visually stimulate the virtual hand: a feather which stroked the dorsal and palmar sides of the virtual hand during the period of illusion induction and a virtual hammer, employed as a threat-inducing object. The Ultrahaptics mid-air haptic stimulation was integrated into the virtual environment employing hand tracking and Unity3D animations. Therefore, the real hands were perfectly mapped onto the virtual hand and multimodally stimulated at precisely the same spatial coordinates. This resulted in greater experimental control over the spatio-temporal synchronicity between the tactile and visual stimulation compared to experiments employing manual brush stroking, where delays due to human errors are common [73]. A neutral Unity3D scene was employed to display the questionnaire. Screenshots of the virtual environments are presented in Figures 2 and 3.

Figure 2. Classroom environment including the virtual hand stimulated by the virtual feather on the dorsal (A) and palmar (B) side and hit by the hammer (C).

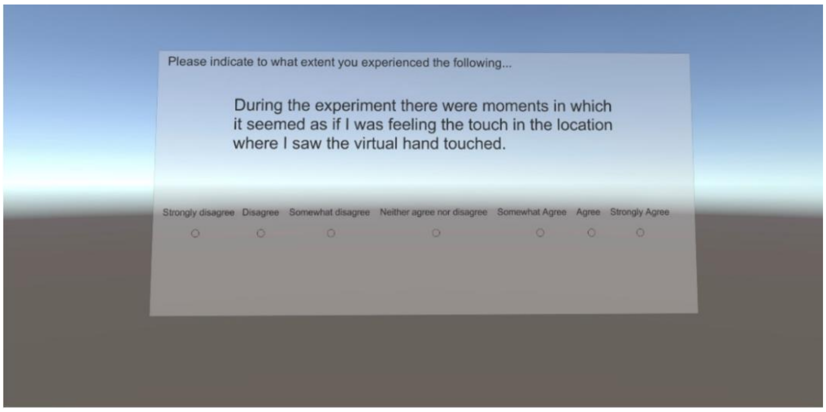

Figure 3. Virtual scene displaying the questionnaire

Participants were immersed in the virtual environment using a head-mounted display (HMD), the Oculus Rift. The Oculus Rift has two screens with 960*1080 pixels resolution per eye. This type of HMD can render content produced in Unity3D in a perceptually more immersive manner compared to other VR systems such as Google cardboard or standard 3DTV monitors [15].

The mid-air haptic stimulation was produced by the Ultrahaptics STRATOS Explore Development Kit (now Ultraleap). The Ultrahaptics device has a 256-transducer array and a Leap Motion camera module, which allowed hand tracking. This feature was essential for accurately displaying the palmar and dorsal sides and movement. The Ultrahaptics projected focused ultrasound of 40 kHz frequency which was modulated at a perceivable frequency of 75 Hz [17], with the pressure amplitude at the tactile point of one (the maximum possible output value). After repeated trials in a pilot study, this frequency was deemed optimal in terms of the tactile intensity and the noise produced by the Ultrahaptics device, which was minimised, thus not interfering with the experimental manipulations. The sound that was still audible was constant in all of the conditions, thus not accounting for any synchrony differences. Moreover, this frequency is within the detection range of both Meissner and Pacinian mechanoreceptors [71]. A BioPac MP36, which is a physiological data acquisition device, was used to record participants' SCRs. The MP36 Four Channel Data Acquisition Unit received signals from the two EL507 electrodes which were placed on participants' non-stimulated left index and middle fingertips and was connected to the Alienware Area-51 gaming PC which was running the BioPac Student Lab (BSL) software. Isotonic gel (GEL101) was employed to increase the data acquisition efficacy of the electrodes. The experimental setup is presented in Figure 4.

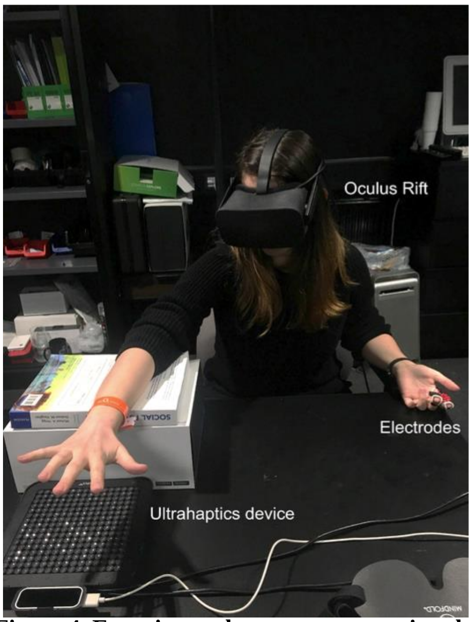

Figure 4. Experimental setup encompassing the Ultrahaptics device, Oculus Rift and Biopac electrodes

The questionnaire, which is included in the Appendix, had responses recorded using Qualtrics Survey Software. There were three questions related to participants' demographic information including sex, age and occupation. The next questions were adapted from the E-WHQ [28] and were employed to determine participants' handedness. Participants were asked to indicate which hand or foot they used to perform 21 activities including holding a paintbrush or using a hammer on a five-point Likert scale with the options: "Always left", "Usually left", "Almost exactly equal", "Usually right" and "Always right". The next parts of the questionnaire were displayed in VR. We opted to present the questionnaire directly in VR because the ratings on questionnaires completed in VR and real-world settings do not seem to be influenced by the context where the questionnaire is administered [79]. Moreover, in this case, VR administration was the most time-efficient and practical option.

There were nine questions adapted from Botvinick and Cohen [8] that were rated on a seven-point Likert scale with options ranging from one (*Strongly disagree*) to seven (*Strongly agree*). In order to match the context of the current study, some changes to the original questionnaire were introduced. More specifically, the term "rubber hand" was replaced with "virtual hand" in items such as "During the experiment, there were moments in which it seemed as if I were feeling the touch in the location where I saw the virtual hand touched" and "During the experiment there were moments in which I felt as if the virtual hand was my own hand". The term "paintbrush" was replaced with "virtual feather" "During the experiment, there were moments in which it seemed as if what I was feeling was caused by the virtual feather that I was seeing on the screen." The aforementioned questions were related to the VHI, whilst the following six questions were unrelated to the illusion.

Four questions adapted from Egan et al. [23], which are also included in the Appendix, were related to immersion in VR. The question used for further analysis was "I was immersed in the environment." Participants rated these questions on a visual analogue scale ranging from zero (*Strongly disagree*) to 100 (*Strongly agree*). A visual analogue scale was employed instead of the five-point Likert scale used by Egan et al. [23] in order to increase the precision with which individuals' experiences in VR could be captured and also because it generated interval-level measurement data which was more suitable for the statistical analysis performed [88]. Finally, two questions, "The touch I was feeling was intense" and "The touch I was feeling was in the same location as what I was seeing", were added in order to quantitatively describe the tactile intensity and location of the mid-air haptic stimulation experienced by the participants. They were rated on a visual analogue scale ranging from zero (*Strongly disagree*) to 100 (*Strongly agree*).

2.3 Design

The current study employed a within-subjects design. The dependent variables were the strength of the VHI measured through a self-report questionnaire as well as SCRs, perceived tactile intensity and perceived immersion. SCRs were chosen as the objective VHI measure due to the high reliability of this measure compared to proprioceptive drift, which has been preponderantly employed in similar past studies inducing the VHI using automated tactile stimulation e.g., [3, 72, 73]. One of the independent variables was the type of visuo-tactile stimulation applied, either synchronous or asynchronous. In the asynchronous conditions, the visual and haptic stimulation had the same time of stimulus onset, but they were 180° out of phase. When the visual stimulation started at the fingertips, the haptic stimulation started at the wrist and vice versa. The second independent variable was the location of the stimulation, on the palmar or the dorsal surface of the hand. This study received ethical approval from the University of Bath Psychology Research Ethics Committee.

2.4 Procedure

Five participants took part in the pilot study which was conducted before the main data collection phase of the study. The pilot was conducted under the exact same conditions as the main experiment in order to assess the feasibility of the experimental set-up. Because no considerable changes were made, the data generated from these participants was included in the final analysis.

Participants read the information sheet and gave informed consent by signing the consent form. They then completed the demographics parts of the questionnaire and the E-WHQ. Following this, participants were guided to the VR laboratory where the experimenter blindfolded them in order to ensure that they would not see the experimental setup and guided them to a chair. After applying the isotonic gel to the electrodes, the experimenter attached them to participants' fingertips. Participants were then directed to close their eyes, remove the blindfold and place the HMD on their head before opening their eyes. They were asked to adjust the HMD until it felt comfortable and the visual clarity was maximised. A five-minute period necessary for the optimisation of the electrodes was spent further describing the study and answering questions. This was followed by the start of the first condition.

Each participants' hand was tracked in real time by the Ultrahaptics camera hardware. Amplitude modulation was used to generate the stimulus with a frequency of 75 Hz. The system detects the wrist, the knuckle and fingertip joints for each finger. As illustrated in Figure 5, the focal point of modulation travelled linearly along a path from the wrist joint to the fingertip, interpolating between each joint of the index finger at the constant speed of 0.1 meters/s. When it reached the fingertip, the stimulation started a new cycle at the wrist joint. As the hardware detects and tracks the hand in real time, the distance between joints was tailored to each participant automatically by the software. The total stimulation time for each trial was 2 minutes and 30 seconds for each participant, sufficient for inducing a compelling VHI [4], so participants experienced slightly different repeat counts based on their hand size.

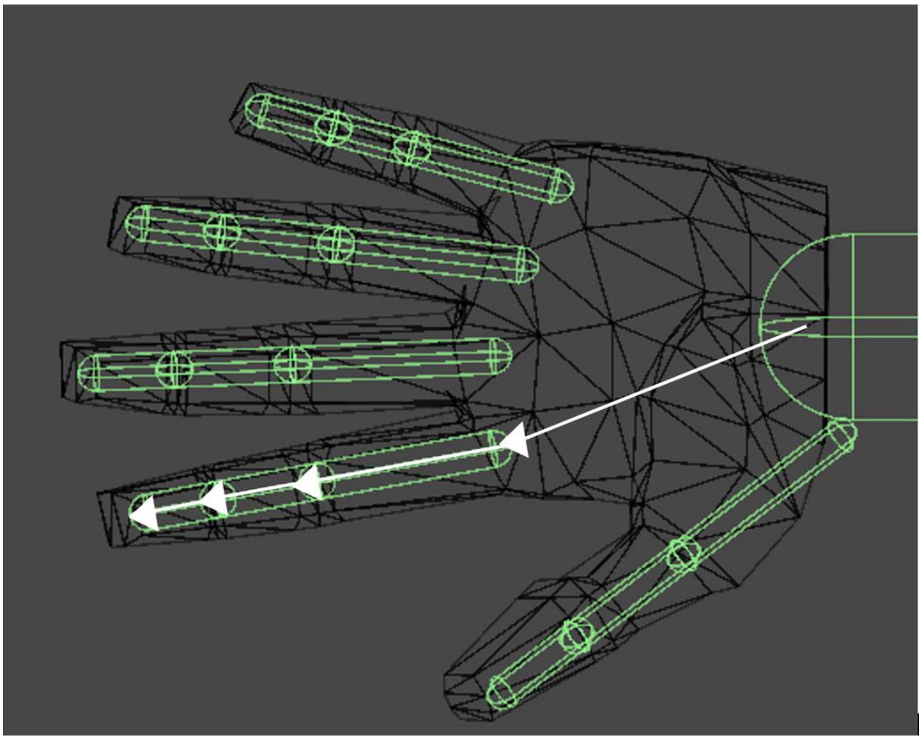

Figure 5. Hand model showing the wrist, knuckles and fingertip joints. The white line represents the trajectory of the focal point stimulation starting from the wrist joint and going towards the fingertip. The arrows indicate the direction of the stimulation.

There were four visuo-tactile stimulation conditions presented in a counterbalanced order to compensate for potential order effects: palmar synchronous, palmar asynchronous, dorsal synchronous and dorsal asynchronous. All participants experienced each of the four conditions once. At the beginning of each condition, the experimenter instructed the participants to place their right hand on a customised hand rest, with the palm either facing downwards or upwards at a distance of approximately ten centimeters above the Ultrahaptics device, which is within its optimal working range [71]. Participants were instructed to keep their hands completely still during each period of visuo-tactile stimulation. After placing their hands in the correct position, the experimenter shifted the virtual viewpoint to match with the HMD's real-world position and orientation with a key press. This ensured that the virtual and real hand were spatially aligned. After the positional calibration, the experimenter pressed another key in order to start the visuo-tactile stimulation. Each induction period was followed by the fall of the virtual hammer. The experimenter marked the hammer fall on the SCR graph with a key press in all conditions. In each condition, after the hammer fall, participants saw the questionnaire and the experimenter reinforced that there were no right or wrong answers and that the answers needed to describe participants' experiences as accurately as possible. Participants indicated their responses verbally and the experimenter entered them into Qualtrics. Finally, participants read the debrief sheet, received £10 as remuneration and completed the participant payment forms. The experiment duration typically ranged from 30 minutes to 45 minutes.

2.5 Analysis

As SCRs are generally recorded from the non-dominant hand [18], we excluded left-handed participants, whose SCRs were recorded from their dominant hand, from the final analysis. Moreover, in order to control for any sex-related variability in RHI reports [33] and vibrotactile intensity reports [56], male participants were also excluded from the final analysis. This resulted in a final sample for the subjective measures of 41 participants composed of right-handed females with a mean age of 20.44 (SD = 2.14).

As previously suggested [83], the comparison between the three VHI-related questions in the synchronous and asynchronous conditions is the most suitable VHI indicator. As a result, we focused our main analysis on the first three VHI-related questions, as well as the perceived immersion and perceived tactile intensity questions, as they were deemed the most relevant items for our research aims. For the control questions, in the Supplementary Materials section, we added four boxplot figures showing the ratings on all of the VHI questions. We also added a table showing the descriptive stats for the remaining measures (enjoyment of the VR experience, perceived realism of the VR environment, sense of presence and extent to which the visuo-tactile stimulation was perceived in the same location).

We obtained the mean score of the three VHI-related questions, which was used for further analysis. As revealed by Shapiro-Wilk tests, the data in the palmar synchronous (S-W = .93, df = 41, p = .012), palmar asynchronous (S-W =.89, df = 41, p = .001), dorsal synchronous (S-W = .90, df = 41, p =.002) and dorsal asynchronous (S-W =.93, df = 41, p =.021) conditions were not normally distributed. However, due to ANOVA being robust to violations of normality [7] and to the within-subjects design, a 2 (type: synchronous versus asynchronous) x 2 (location: palmar versus dorsal) repeated-measures ANOVA was performed on VHI questionnaire ratings. The interaction was further investigated employing the non-parametric Wilcoxon rank-sum test. Based on the aim of the current study, the a priori contrasts between the palmar synchronous and palmar asynchronous, dorsal synchronous and dorsal asynchronous, palmar synchronous and dorsal synchronous as well as palmar asynchronous and dorsal asynchronous conditions were explored. Similarly, 2 (type) x 2 (location) ANOVAs were performed to investigate the effect of condition on perceived tactile intensity and perceived VR immersion ratings.

For the SCR data, the mean SCR from three and one seconds before the hammer fall, as a baseline interval, were subtracted from the mean SCR from one and six seconds after the hammer fall [26]. This region of interest was chosen because stimulus-elicited SCRs typically occur between one and three seconds after stimulus onset [18]. SCR amplitudes below 0.05 μs were scored as zero responses [11, 18] and participants who had zero responses in more than half of the conditions were excluded from the analysis [cf., 26]. This left 36 participants for the final SCR analysis. All data were standardised by dividing each raw SCR value by the participant's mean SCR to control for individual differences in responsivity and to enable comparisons across participants [5, 10]. Despite standardised SCR data not having a normal distribution in the palmar synchronous (S-W = .84, df = 36, p < .001) and dorsal asynchronous (S-W = .93, df = 36, p = .027) conditions, a 2 (type: synchronous versus asynchronous) x 2 (location: palmar versus dorsal) repeated-measures ANOVA was performed on the standardised SCR values due to the aforementioned robustness of the test.

3 Results

For mean VHI, perceived tactile intensity, perceived immersion ratings and standardised SCR values for the four conditions, please refer to Table 1.

Table 1. Means and Standard Deviations (SD) for VHI, Perceived Tactile Intensity, Perceived Immersion Ratings and Standardised SCR Values for All Conditions

Condition	VHI rating	Tactile Intensity	Immersion	Standardised SCR
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*
Palmar synchronous	5.97 (.76)	56.61 (22.38)	76.02 (12.73)	1.09 (.72)
Palmar asynchronous	4.84 (1.71)	50.19 (21.58)	70.97 (14.71)	.85 (.51)
Dorsal synchronous	5.55 (1.01)	44.71 (22.87)	75.02 (14.64)	1.00 (.51)
Dorsal asynchronous	4.93 (1.40)	39.39 (20.92)	70.34 (16.96)	1.05 (.57)

3.1 Questionnaire measure

The 2 (type) x 2 (location) repeated-measures ANOVA performed on VHI ratings revealed a significant main effect of type of stimulation, F (1, 40) = 20.08, p<.001, partial η^2 = .33, with the VHI ratings in the synchronous conditions (M = 5.76, SD = .91) significantly higher than in the asynchronous conditions (M = 4.89, SD = 1.56). The main effect of location was not significant, F (1, 40) = .89, p = .351, thus VHI ratings did not significantly differ when the palmar side (M = 5.41, SD = 1.43) was stimulated compared to the dorsal side (M = 5.24, SD = 1.25). The interaction between type and location on VHI ratings was significant, F (1, 40) = 4.48, p = .041, partial η^2 = .10, and is illustrated in Figure 6.

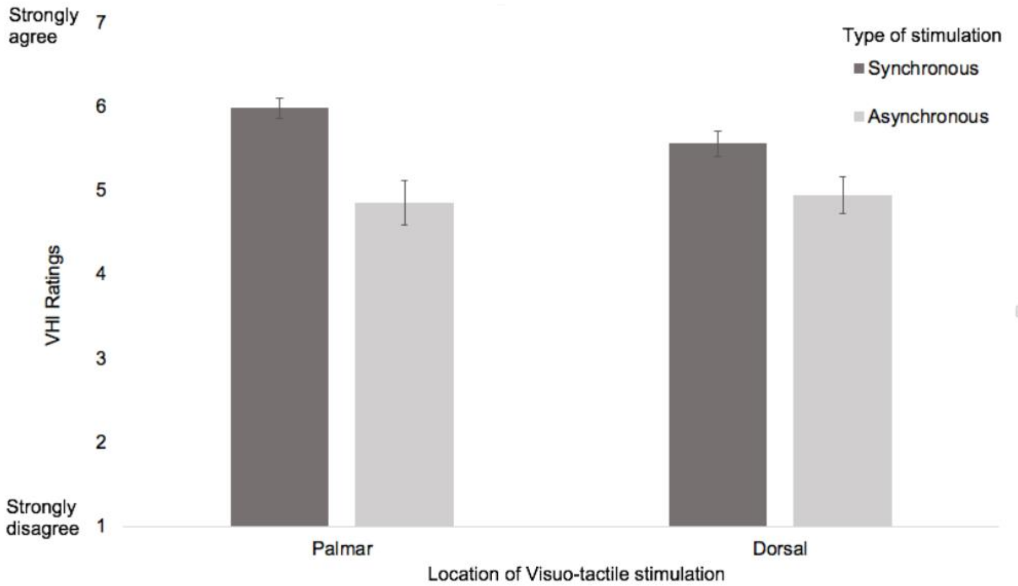

Figure 6. Mean VHI ratings, as a function of type and location of visuo-tactile stimulation. Error bars represent standard error of the mean (SEM)

For the palmar conditions, VHI ratings were significantly higher in the synchronous (Mdn = 6.00, IQR = 1.17) compared to the asynchronous (Mdn = 5.33, IQR = 2.17) condition (Z = -3.76, p < .001). For the dorsal conditions, VHI ratings were significantly higher in the synchronous (Mdn = 5.67, IQR = 1.00) compared to the asynchronous (Mdn = 5.33, IQR = 1.42) condition (Z = -3.39, p = .001). VHI ratings were significantly higher in the palmar synchronous condition (Mdn = 6.00, IQR = 1.33) compared to the dorsal synchronous (Mdn = 5.67, IQR = 1.00) condition (Z = -2.95, p = .003). Conversely, the difference in VHI ratings between the palmar asynchronous (Mdn

= 5.67, *IQR* = 2.42) and dorsal asynchronous (*Mdn* = 5.33, *IQR* = 1.42) conditions was not significant (Z = -.12, p = .904).

The 2 (type) x 2 (location) repeated-measures ANOVA performed on perceived tactile intensity ratings showed that there was a significant main effect of stimulation type, F (1, 40) = 9.13, p = .004, partial η^2 = .19, with significantly higher perceived intensity ratings in the synchronous (M = 50.65, SD = 23.27) compared to the asynchronous (M = 44.79, SD = 21.81) conditions. Furthermore, the main effect of location was also significant, F (1, 40) = 15.38, p < .001, partial η^2 = .28, showing significantly higher perceived intensity ratings when the palmar side (M = 53.40, SD = 22.08) compared to the dorsal side (M = 42.05, SD = 21.94) was stimulated. The interaction between the type and location of stimulation was not significant, F (1, 40) = .09, p = .764. This is illustrated in Figure 7.

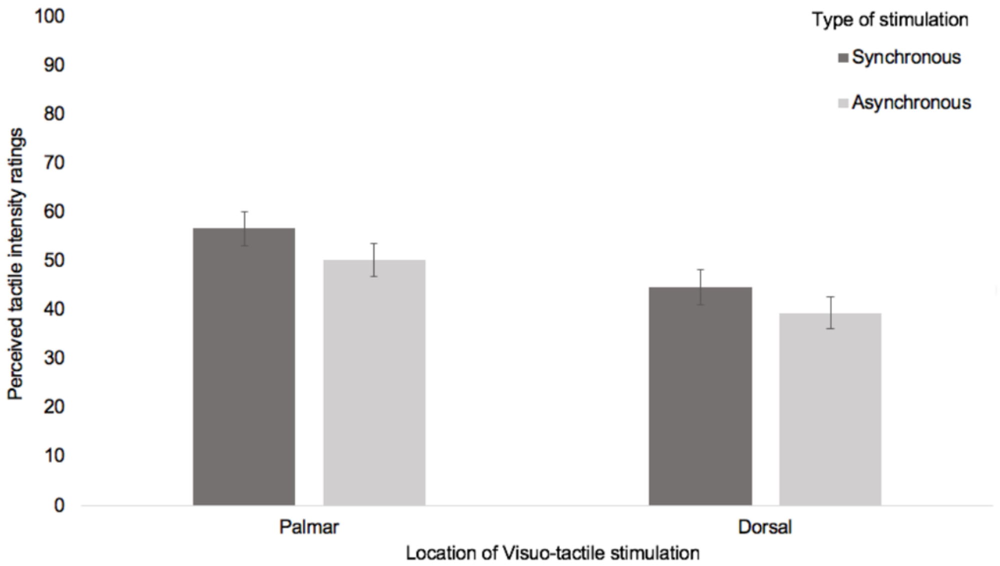

Figure 7. Mean perceived tactile intensity ratings, as a function of type and location of visuo-tactile stimulation. Error bars represent standard error of the mean (SEM)

The 2 (type) x 2 (location) repeated-measures ANOVA performed on perceived immersion ratings revealed a significant main effect of type of stimulation, F (1, 40) = 5.97, p = .019, partial η^2 = .13, with overall significantly higher immersion ratings in the synchronous (M = 75.52, SD = 13.64) compared to the asynchronous (M = 70.66, SD = 15.78) conditions. The main effect of location on immersion ratings was not significant, F (1, 40) = .20, p = .653, and so was the interaction between type and location of stimulation, F (1, 40) = .025, p = .874. This is illustrated in Figure 8.

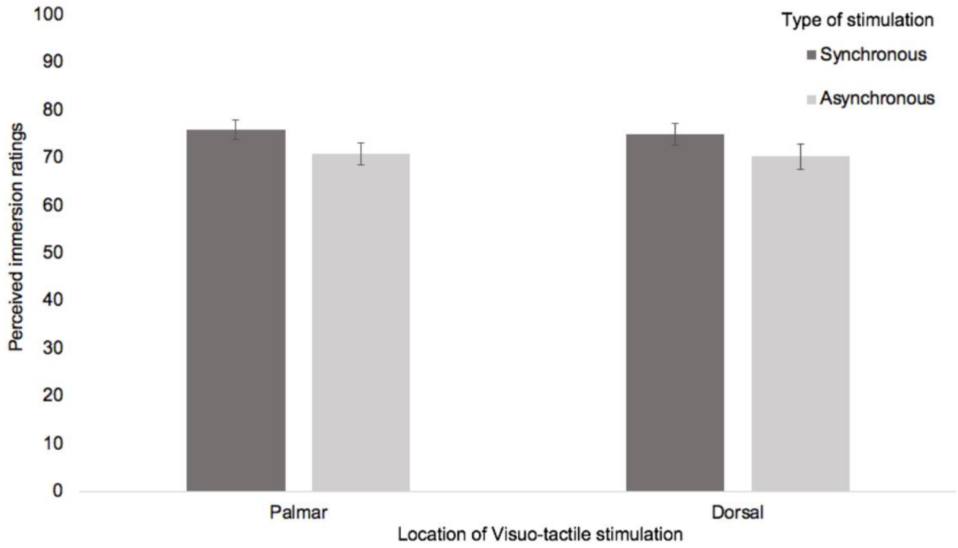

Figure 8. Mean perceived immersion ratings, as a function of type and location of visuo-tactile stimulation. Error bars represent standard error of the mean (SEM)

3.2 SCR measure

The 2 (type) x 2 (location) repeated-measures ANOVA performed on the standardised SCR values revealed a non-significant main effect of stimulation type, F (1, 35) = 1.15, p = .290 and a non-significant main effect of location of stimulation, F (1, 35) = .16, p = .687. The interaction between type and location of stimulation was also not significant, F (1, 35) = 1.52, p = .225, and is illustrated in Figure 9.

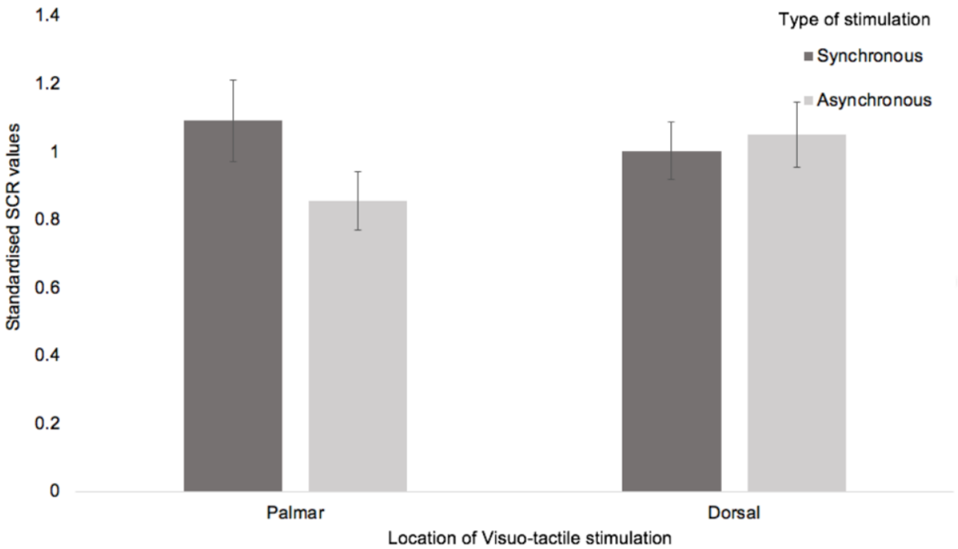

Figure 9. Mean standardised SCR values, as a function of type and location of visuo-tactile stimulation. Error bars represent standard error of the mean (SEM)

In order to account for potential "surprise" effects triggered by the first hammer fall, we employed two repeated-measures one-way ANOVAs with condition order (first vs second vs third vs fourth) as the variable on standardised SCRs in palmar-synchronous and dorsal-synchronous conditions. This allowed us to compare the SCRs in trials where the palmar-synchronous and dorsal-synchronous conditions were presented first to SCRs in trials where the palmar-synchronous and dorsal-synchronous, respectively, were presented later in the succession of conditions. For the palmar-synchronous conditions, Mauchly's test indicated that the assumption of sphericity had not been violated (χ^2 (5) = .006, p = .162), so no correction was applied. Standardised SCR values were not significantly affected by the order of the palm-synchronous condition, F (3, 9) = .82, p = .515. For the dorsal-synchronous conditions, Mauchly's test indicated that the assumption of sphericity had been violated (χ^2 (5) < .001, p = .043), therefore degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity (ε = .36). Similarly, standardised SCR values were not significantly affected by the order of the dorsal-synchronous condition, F (1.087, 3.261) = .34, p = .613. Overall, SCRs were not affected by the order of the conditions.

4 Discussion

Our study investigated the induction of the VHI by applying ultrasonic mid-air haptic stimulation produced by an Ultrahaptics device to the glabrous skin on the palmar surface of the hand and the hairy skin on the dorsal surface. Additionally, we explored the relationship between synchronous visuo-tactile feedback, illusory body ownership and perceived immersion in VR. The subjective VHI experience was stronger when synchronous visuo-tactile stimulation was provided compared to asynchronous stimulation, in line with H1. This finding corroborates previous real-life and VHI studies [12, 30, 67].

Further investigating the results, the VHI ratings were over the middle of the scale for both the synchronous and asynchronous conditions. This means that participants experienced a certain degree of the illusion in all conditions, possibly due to the immersive environment and the first-person perspective that allowed their real hand and the virtual hand to be co-located, which is in line with previous research [42, 44, 67]. Therefore, the VHI seems to have been disrupted by the asynchronous stimulation rather than strictly being gradually induced by the synchronous stimulation. Therefore, the VHI may have been disrupted by the asynchronous stimulation rather than strictly being gradually induced by the synchronous stimulation. Future work may investigate this by using a technique to gradual enhance the degree of realism of the virtual environment through virtual human behaviour and environment coherence [81].

In synchronous conditions, the VHI was stronger when the palmar side was stimulated compared to the dorsal side. As other bottom-up and top-down parameters were maintained constant throughout the experiment, this suggests that VHI strength was modulated by the tactile skin sensitivity to mid-air haptic stimulation. However, in asynchronous conditions, VHI strength was similar when the palmar and dorsal sides were stimulated, *illustrating that the asynchrony diminished the illusion in both cases*. Overall, these findings reveal that mid-air haptic stimulation can successfully induce the VHI both when the dorsal side, and the palmar side of one's hand are stimulated. This is particularly remarkable considering recent evidence suggesting that VR potentially acts as a distractor which increases tactile perception thresholds [47].

In line with H2, the mid-air haptic stimulation was perceived as more intense when it was administered to the palmar compared to the dorsal side of the hand. This lends credence to the suggestion that the VHI was stronger when the palmar side was stimulated compared to the dorsal side due to tactile sensitivity differences. Additionally, when it was synchronous with the feather, the mid-air haptic stimulation was perceived as more intense than when it was asynchronous. This adds a subjective dimension to psychophysical studies suggesting that multisensory integration leads to the convergence of feedforward signals coming from distinct modalities, which boosts their perceived intensity [1, 2, 31]. It is important to note that in the current study, skin sensitivity was not manipulated, it was solely measured, which enabled a comparison between conditions. To our knowledge, the role of the perceived intensity of the haptic stimulation has not been investigated for the RHI or the VHI. Future research should systematically manipulate the intensity of the haptic stimulation by modulating the amplitude of the Ultrahaptics stimulus. This technology would be ideal for this type of investigation due to the high level of control over the stimulus intensity it enables.

Consistent with H3, the classroom virtual environment was perceived as more immersive in the synchronous conditions compared to asynchronous conditions. This provides empirical support for Slater's [82] suggestion that congruent sensorimotor feedback is a key contributor to VR immersion potentially by making the VR environment seem more realistic. Although in the palmar synchronous condition the subjective VHI was stronger than in the dorsal synchronous condition, this was not true for perceived immersion. Thus, illusory body ownership and perceived immersion were not directly linked but they were both modulated by the synchrony of visuo-tactile feedback (see Figure 1).

Regarding the physiological measure, the SCRs generated by the hammer fall did not significantly differ across conditions. Thus, SCRs were not related to subjective body ownership and were likely the effect of VR presence [44, 77]. This finding disagrees with H1 and several real-life [4, 64] and VHI studies [95], but in line with other VHI studies [44, 53, 94]. Employing a VHI paradigm and either non-painfully hitting the virtual hand with a ball or cutting it with a knife, Ma and Hommel [53] distinguished between the SCR effects induced by these two events. In line with previous research employing low-threat stimuli such as the fall of a virtual lamp [95], SCRs were significantly higher when the hand hit by the ball had been embodied than when it had not been embodied. Conversely, SCRs were not related to ownership when the virtual hand was injured by the knife. Ma and Hommel [53] suggested that highly threatening events, such as the knife or hammer fall, are processed differently and lead to equal autonomic activity when targeting embodied and non-embodied hands. However, this suggestion does not account for findings reported in real-life RHI studies which employed stimuli arguably as threatening as the knife or hammer such as a paper-cutter and found increased SCRs for embodied rubber hands [64]. Alternatively, it could be that the hammer fall is a rapid, one-shot discrete event, while the cut is a continuously pain-inducing experience, which would drive a longer SCR that could be more accurately recorded.

This study employed a highly controlled sample solely composed of right-handed females. This eliminated sex-specific variability in RHI self-reports [33, 52] and in subjective reports of vibrotactile intensity of stimuli applied to the hand and arm [56] previously reported in the literature. Moreover, using this sample balanced out the bias in several VHI studies which exclusively focused on the VR and VHI experience of males [e.g., 51, 83, 86]. Although beyond the scope of the current study, sex-related and handedness-related differences in the VHI and ultrasonic mid-air haptic experiences are important areas of research that should be further explored in the future in order to understand how users' experiences with VR and haptic technologies might differ based on their characteristics, which could inform developers.

Further examining the current sample, an issue identified during informal post-experiment conversations was related to participants' skin tone. Four participants verbally reported to the experimenter that their skin tone did not match the virtual hand, and this prevented them from perceiving the virtual hand as belonging to them. This observation is in line with Lira et al. [50] who suggested that providing synchronous stimulation on a black rubber hand induced a considerably less vivid RHI compared to a white rubber hand in a sample of white participants. However, several RHI [26] and VHI studies [35, 55, 65] suggested that different and same colour hands and bodies can be embodied to the same extent, especially at an unconscious level revealed by behavioural and physiological measures. Thus, the perceived skin tone difference of four participants is unlikely to have influenced the findings of this study.

Another crucial methodological element to consider is the sensorimotor synchrony. In our work, it was possible to apply visuo-tactile stimulation at precisely the same spatio-temporal coordinates via a software-controlled interface. This ensured greater experimental control over the synchronicity between the tactile and visual stimulation compared to real-life RHI studies [73]. Additionally, the tactile intensity and frequency of the mid-air haptic stimulation were constant in all conditions. However, the visuo-motor synchronicity between the real and virtual hand was less rigorously controlled for. Involuntary hand tremors might have occurred potentially due to the arm position required for this study, providing synchronous visuo-motor feedback. This is a paramount issue as synchronous visuo-motor feedback appears to induce body ownership over rubber [22] as well as virtual hands and bodies [42, 78], even to a greater extent than synchronous visuo-tactile stimulation [44]. This might have interfered with the effects of the visuo-tactile stimulation. Nevertheless, according to [44], who investigated the interplay between synchronous and asynchronous visuo-motor and visuo-tactile stimulation on VHI strength, discrepancies in either visuo-tactile or visuo-motor feedback are equally as powerful in disrupting the illusion. Thus, in the current study, although establishing visuo-motor synchrony might have inflated the VHI strength in certain instances, this would not have impacted the effect of the manipulation employed.

The current study has potential multidisciplinary implications. Generally, it seems that having a self-avatar and receiving the attachment-free, dynamic and precise mid-air haptic stimulation led participants to perceive the virtual environment as immersive, as also suggested by previous research on the individual elements of the current VR experience [48, 71, 87]. This reveals the applicability of mid-air haptic stimulation for creating immersive VR experiences. Moreover, this study could inform the design of more immersive virtual environments by underlining the importance of the synchronicity between felt and seen stimuli in VR. This might be crucial for increasing the clinical effectiveness of VR [12, 29]. In a mental health context, the efficacy of VR exposure therapy for phobic patients could be enhanced by increasing user's feelings of immersion in virtual environments, where situations that are safer but functionally and perceptually like the real world could be created [13, 76]. For example, with this experimental setup, individuals who have a spider phobia could first experience a period of synchronous visuo-tactile stimulation which would increase their feelings of immersion before being gradually exposed to a virtual spider. Furthermore, from a different clinical perspective, seeing a co-located and embodied virtual hand might have analgesic effects [58]. The intensity of the analgesic effects seems to be correlated with illusory ownership strength [25]. Thus, to maximize VHI strength and associated analgesic effects, the finding that the VHI might be modulated by skin sensitivity could guide VHI induction. In the context of ultrasonic mid-air haptic stimulation, this would translate into applying synchronous visuo-tactile stimulation on glabrous skin, but this might vary based on the characteristics of the touch employed and the anatomical properties of the skin stimulated.

Thus, we acknowledge additional anatomical differences between glabrous and hairy skin which might modulate the RHI [16, 91]. C-tactile afferent fibers, which are involved in processing pleasant touch, innervate hairy skin and are absent from glabrous skin [61]. Van Stralen et al. [91] manually delivered synchronous and asynchronous tactile stimulation either rated as affectively neutral or pleasant on the dorsal and palmar surface of participants' hand and a rubber hand. They reported a stronger RHI revealed by proprioceptive drift when the type of touch rated as pleasant stimulated the hairy skin compared to regular touch, but no difference in RHI strength between pleasant and regular touch when the glabrous skin was stimulated. According to Van Stralen et al. [91], these findings illustrate the involvement of C-tactile fibres in RHI modulation. This is particularly intriguing as Obrist, Subramanian, Gatti, Long and Carter [60] suggested that Ultrahaptics stimuli can convey the sensation of pleasantness with specific frequency, location and intensity settings. Therefore, providing Ultrahaptics stimuli perceived as pleasant could potentially interfere with the current findings. They might compensate for the reduced sensitivity of hairy skin and lead to equal or even increased RHI intensity on the dorsal compared to the palmar surface. These speculations constitute an intriguing avenue for future research which could exploit the array of properties afforded by Ultrahaptics technology to understand the influence of the anatomical differences between hairy and glabrous skin on the RHI.

Moreover, future research could employ the current technological framework to investigate the interaction between the sense of body ownership and the sense of agency. The sense of agency refers to the feeling of control over one's body movements [34]. Agency can be induced by providing synchronous visuo-motor feedback in active RHI paradigms, where the fake hand moves in synchrony with the real hand [12]. Together with body ownership, agency is an essential component of embodiment and self-awareness [43]. With a few exceptions e.g. [41, 73, 96], the interplay between body ownership and agency has received less empirical attention than each of them independently [68]. Possibly due to technical difficulties, the understanding of the effects of visuo-tactile and visuo-motor feedback on agency and ownership also seems under-developed [38]. Employing the current experimental setup, parameters related to the visuo-motor and visuo-tactile stimulation could be concomitantly manipulated to explore their independent and integrated influence on both agency and ownership. For instance, participants could reach towards and press a virtual button (visuo-motor feedback) which would generate a tactile sensation (visuo-tactile feedback), as this is one of the default applications of the Ultrahaptics system. In this context, the individual and combined impact of agency and ownership on feelings of immersion could also be investigated. Thus, the limitation of this study related to the synchronous visuo-motor feedback could become a key strength of a future study.

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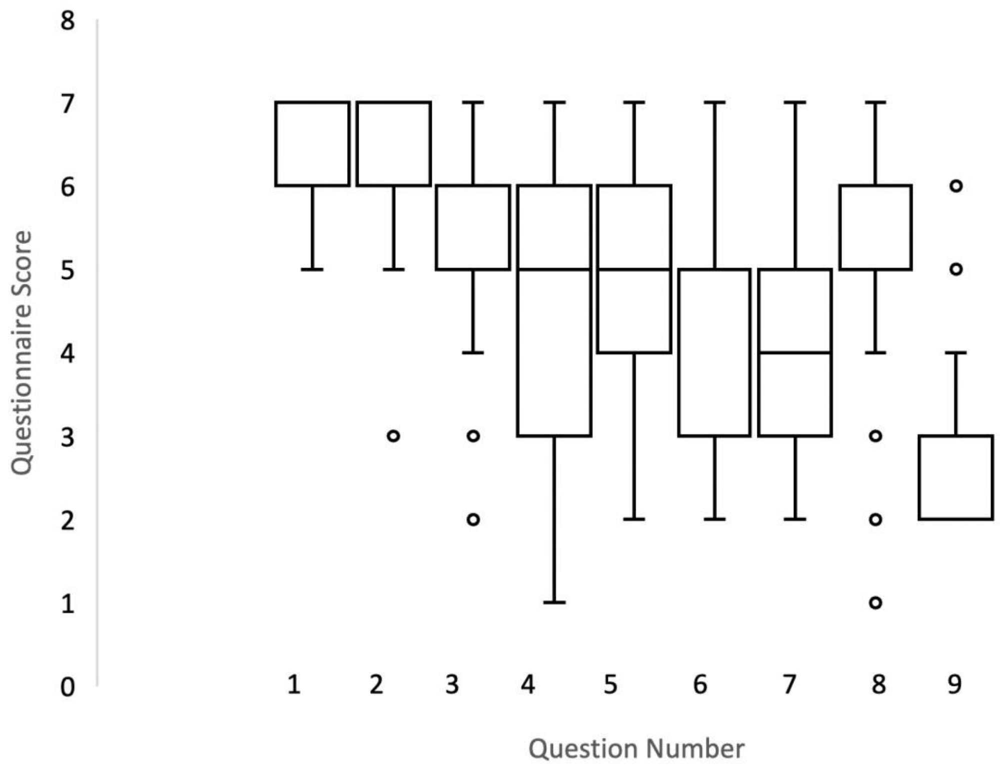

Figure 1. Boxplot for the VHI questionnaire responses in the palmar synchronous condition. Questions 1, 2 and 3 address the illusory experience. The medians are shown, and the boxes are the interquartile ranges (IQR). The whiskers represent the 1.5 × IQR. The datapoints outside the whiskers are the outliers.

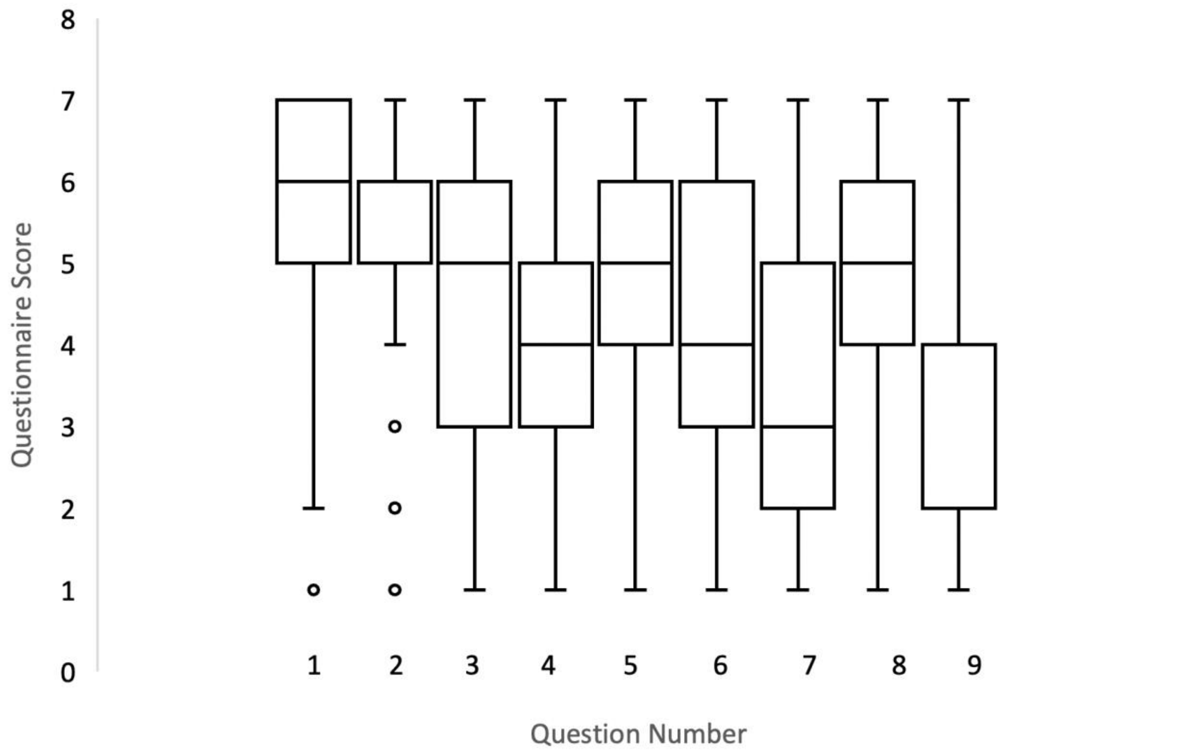

Figure 2. Boxplot for the VHI questionnaire responses in the palmar asynchronous condition. Questions 1, 2 and 3 address the illusory experience. The medians are shown, and the boxes are the interquartile ranges (IQR). The whiskers represent the 1.5 × IQR. The datapoints outside the whiskers are the outliers.

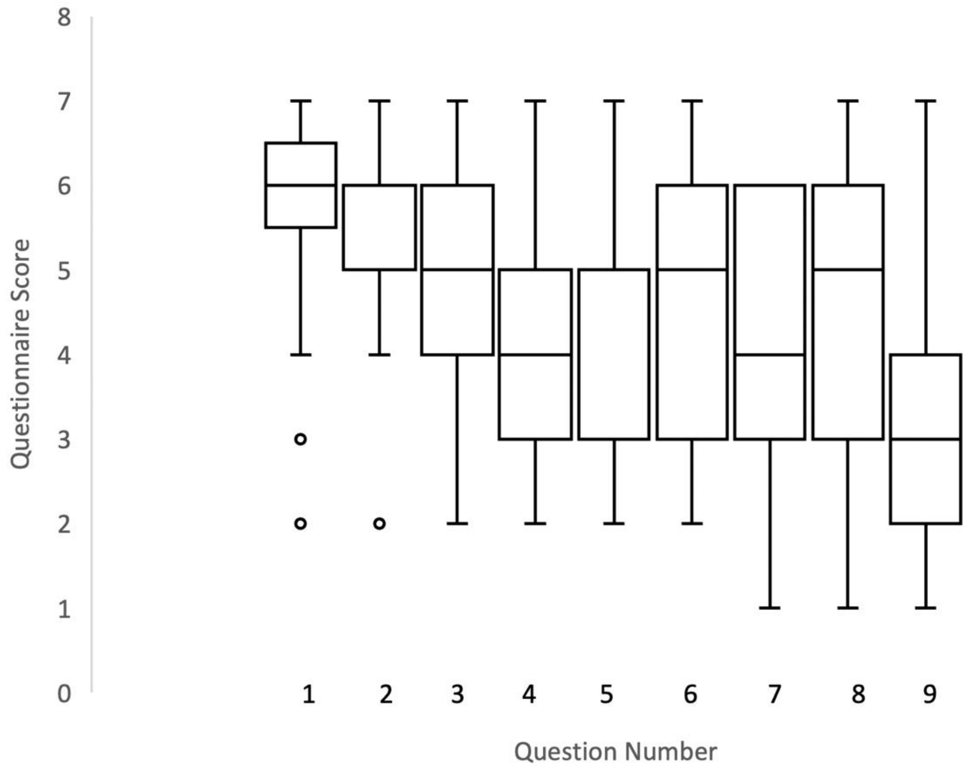

Figure 3. Boxplot for the VHI questionnaire responses in the dorsal synchronous condition. Questions 1, 2 and 3 address the illusory experience. The medians are shown, and the boxes are the interquartile ranges (IQR). The whiskers represent the 1.5 × IQR. The datapoints outside the whiskers are the outliers.

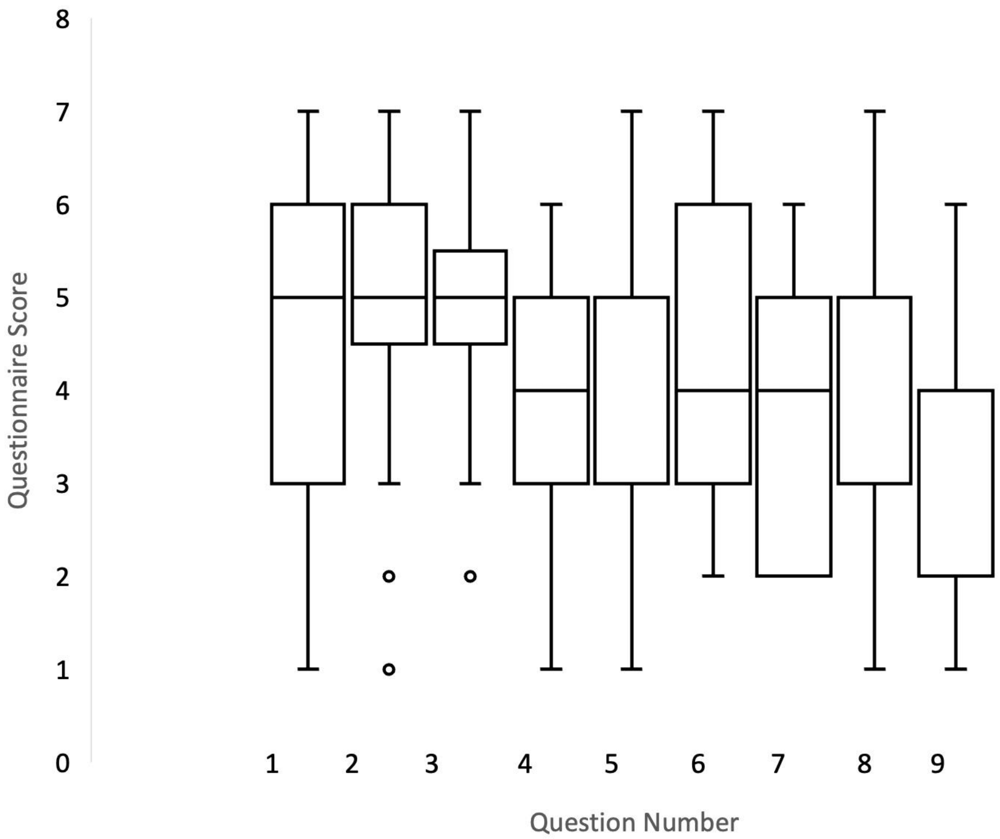

Figure 4. Boxplot for the VHI questionnaire responses in the dorsal asynchronous condition. Questions 1, 2 and 3 address the illusory experience. The medians are shown, and the boxes are the interquartile ranges (IQR). The whiskers represent the 1.5 × IQR. The datapoints outside the whiskers are the outliers.

Table 1. Means and Standard Deviations (SD) for Enjoyment of the VR experience, Perceived Realism of the VR Environment, Sense of Presence and Extent to which the Visuo-Tactile Stimulation was Perceived in the Same Location for All Conditions

	Enjoyment	Realism	Sense of presence	Same location
Condition	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
Palmar synchronous	76.49 (17.02)	64.80 (18.08)	38.00 (17.65)	84.24 (14.68)
Palmar asynchronous	75.61 (17.16)	63.80 (18.02)	41.32 (20.33)	62.93 (31.51)
Dorsal synchronous	75.49 (16.01)	65.44 (16.74)	40.41 (18.81)	73.29 (17.66)
Dorsal asynchronous	73.68 (16.35)	62.93 (16.16)	40.83 (19.17)	58.73 (29.09)