I'm Sensing in the Rain: Spatial Incongruity in Visual-Tactile Mid-Air Stimulation Can Elicit Ownership in VR Users

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ABSTRACT

Major virtual reality (VR) companies are trying to enhance the sense of immersion in virtual environments by implementing haptic feedback in their systems (e.g., Oculus Touch). It is known that tactile stimulation adds realism to a virtual environment. In addition, when users are not limited by wearing any attachments (e.g., gloves), it is even possible to create more immersive experiences. Mid-air haptic technology provides contactless haptic feedback and offers the potential for creating such immersive VR experiences. However, one of the limitations of mid-air haptics resides in the need for freehand tracking systems (e.g., Leap Motion) to deliver tactile feedback to the user's hand. These tracking systems are not accurate, limiting designers capability of delivering spatially precise tactile stimulation. Here, we investigated an alternative way to convey incongruent visual-tactile stimulation that can be used to create the illusion of a congruent visual-tactile experience, while participants experience the phenomenon of the rubber hand illusion in VR.

CCS CONCEPTS

• **Human-centered computing** → *User studies.*

KEYWORDS

Touch, illusions, mid-air haptics, VR, rubber hand illusion, virtual hand illusion, virtual reality, tracking systems

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1 INTRODUCTION

One of the first examples of VR systems was given by Morton Heilig when he created his "Sensorama" in 1962. This was a mechanical multisensory device that was able to render 3D images, sound, tactile stimulation, and smell while projecting a short movie [54]. In 1968, Ivan Sutherland created what is considered to be the first example of a head-mounted display (HMD) system, "the sword of Damocles" [77]. Since then, VR technology has dramatically improved, developing into more portable and visually advanced devices. Today, VR systems are also more affordable and find use in a variety of scenarios, from clinical applications to gaming. Nowadays users can interact with virtual desktops, and we can imagine to provide haptic feedback whenever a user touches an icon by feeling the edges of its shape. Moreover, watching a movie, could go beyond audio-visual stimuli by integrating haptic feedback (see [1, 32]).

A current limitation of VR systems is their lack of haptic feedback. If we want the user to achieve fast and accurate performance while interacting with the environment, enable natural interpersonal interactions (e.g., a handshake between people connected remotely [58]), manage high-dexterity tasks (e.g., operate on a patient at distance), or simply provide an intuitive way to interact with virtual environments (VEs) (e.g., delivering tactile feedback while interacting with a virtual screen [40]), our sense of touch is important and designers need to implement it in VR [66]. There is a general consensus that the integration of haptic feedback increases the immersion in a VE by providing coherence between the knowledge we have of the world and the experience reproduced in VR [8, 29, 53, 67]. Moreover, in 2011 Calleja proposed the Player Involvement Model (PIM) [10], where he suggests that for a player to inhabit a virtual world, he/she needs to be embodied within that world, and he argues for the importance of vision,

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audio and haptic feedback to reach a feeling of presence in the VE.

In recent years, there were attempts by VR companies (e.g., Oculus, HTC, Sony) to implement haptic feedback in their controllers in the form of vibratory feedback. However, the level of presence the user will achieve in a VE depends on the degree of coherence within the context which he/she is experiencing [53]. This means that when we try to convey haptic feedback through additional devices, such as hand-held controllers or haptic gloves, the users' presence could be disrupted. Therefore, it is important that we provide the user with a tactile medium that can be perceived as much as "invisibly" as possible, achieving a "perceptual illusion of non-mediation" [22, 45, 46, 53, 79]. In other words, users need to be unaware of the presence of the tactile device, while still being able to feel the stimulation generated from them.

Mid-air haptic technology offers a new space for touchless interaction. This technology is able to provide haptic feedback leaving the user's hands free to interact with the surrounding (virtual) world by using ultrasound stimulation. Compared to other mid-air devices (airborne and laser-based), ultrasound mid-air haptics have higher spatial and temporal resolution (1 cm, 40 kHz [47]), allows to design complex patterns (static or dynamic) [47], and they are scalable, offering the potential opportunity of covering the entirety of the environment's surfaces. This could allow 360 degree interactions. However, since ultrasound-based mid-air haptics relies on delivering the tactile feedback on the skin from an array of speakers at distance (see Fig. 2), it is crucial to use a precise tracking system (i.e., matching the visual cue in VR). A low precision in the tracking will result in sending the ultrasound stimulation to the wrong location. While the delivery of stimuli in the wrong location is generally disruptive, in VR this is likely to carry the additional drawback of breaking the sense of being in the VE. For instance, in the rubber hand illusion (RHI), it has been shown that an asynchronous or an incongruent visual-tactile stimulation can break the illusion of ownership toward an embodied fake (or virtual) hand [9, 16].

The RHI is the main phenomenon used in psychology to demonstrate the plasticity of our body schema (perception of one's body parts in space) that allows for embodying external objects (e.g., a fake arm/hand). It was firstly studied by Botvinick and Cohen in 1998 [9]. While the participant's hand is kept hidden, a fake one is placed in an anatomically plausible position adjacent to the real hand at a maximal distance of 30 cm [25]. Following a synchronous visual-tactile stimulation of the real and the fake hand (synchronous condition), the participant will perceive the fake hand as his/her own as a result of the embodiment process of the fake hand into the body schema. Conversely, in the case of an asynchronous stimulation of the real and the rubber hand (asynchronous condition) the illusion is lost or it is hardly established. The RHI has also been studied during congruent or incongruent visual-tactile stimulation [17]. When users were stimulated through a congruent visual-tactile stimulation of the real and the fake hand (i.e., users saw their hand touched in the same spot at which they could feel the tactile stimulation) they could embody the fake hand. When the visual-tactile stimulation was incongruent, the embodiment was not established. With the availability of new portable VR systems such as the HMDs, this phenomenon has been broadly extended in VEs (see Related Work section). VR is particularly advantageous for the study of the RHI because it is entirely programmable, hence, controllable. It becomes easy to change the shape of a fake arm, its color, and size, making it possible to investigate the details of this phenomenon [74].

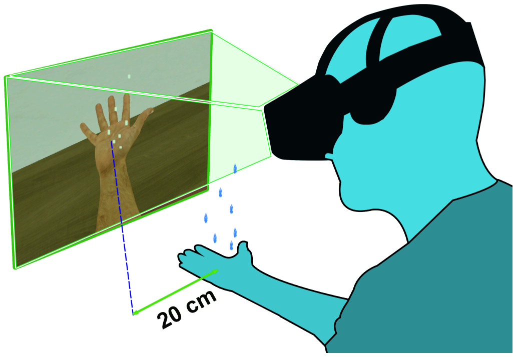

Figure 1: Illustration of the virtual hand illusion (VHI). A virtual arm is displayed in VR at the same height of the participant's hand. Both the virtual and the real arm receive synchronous tactile stimulation (e.g., raindrops simulated by mid-air touch). After few seconds, the participant will embody the virtual hand.

In this paper, we investigate the illusion of falling raindrops that creates the illusion of real rain using mid-air tactile stimulation. To measure the illusion we exploit the phenomenon of the RHI in VR (referred to as VHI, see Fig. 1) using mid-air tactile stimulation. We use, not only the traditional congruent and incongruent visual-tactile stimulation approach, but for the first time exploiting mid-air touch in VR, we also use incongruent multiple stimulations. We demonstrate the occurrence of the illusion even during an incongruent visual-tactile condition, opening up new design explorations that help to overcome the effect of the current limitations of hand-free tracking systems (i.e., imprecise spatial tracking, thus, wrong tactile delivery on the hand). We hypothesize that mid-air touch is the right technology for this first time exploration, due to its controllability and requirement for no physical attachments in VR.

The contributions of this paper are: a) a systematic investigation of the reproducibility of the RHI in VR with real-time

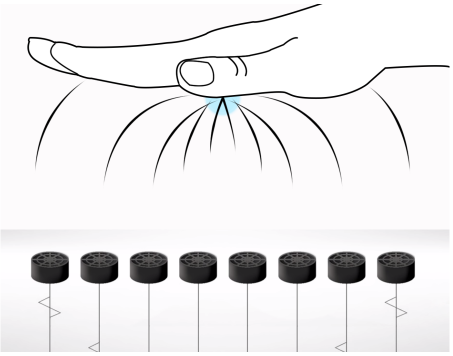

Figure 2: The mid-air haptic technology enables the display of a tactile feedback in mid-air using a series of ultrasonic transducers emitting sound waves that can be felt when they are spatially and temporally aligned, creating a focal point. (*Picture adapted from Ultrahaptics LtD*)

tracking and rendering of the human hand using mid-air tactile stimulation, b) demonstrating whether the illusion occurs with a multiple incongruent and multiple congruent stimulation approach, accounting for c) the relevance of the hand's posture (palm upward vs. palm downward) and d) demonstrating the importance of the stimulation type (tapping vs. stroking).

2 RELATED WORK

In this section, we review related work that makes use of haptic illusions in VR. We will then present the most recent work on the VHI. Finally, we will introduce the mid-air haptic technology and its relevance for the study of the VHI.

Relevance of Illusions to HCI

The implementation of haptic feedback in VR to enhance the immersion of the system represents a challenge. To reach this goal, there are two options. The first is to build a system with a high level of fidelity to the reality (but rendering all the different aspects of the haptic sensation is challenging, and they requires complex hardware). The second is to exploit the knowledge we have of our perceptual system to create perceptual illusions that feel real.

Following the latter direction, recent work has exploited perceptual illusions to render a series of different effects. Kildal presented a technique that gives the haptic illusion of pushing a button when pressing against a rigid surface [39]. Israr and Poupyrev provided an algorithm able to convey a haptic illusory movement on the participants' back using fixed vibrotactile actuators [33]. A similar concept was extended by Zhao et al. in 2015, studying the illusion of movement on handheld tablets [88] and further extended to non-interconnected hands by Pittera et al. [64]. More recently, Zhao et al. made use of the haptic retargeting technique to minimize the user-perceived difference between the physical object and its rendered virtual shape [89]. Whitmire et al. designed the Haptic Revolver, a device that can simulate different texture and shapes in VR [83]. Finally, Feuchtner et al. allowed users to manipulate objects at distance by rendering in VR a virtual stretched arm that participants were able to embody [23].

These are just some examples that demonstrate the interest and benefits of perceptual illusions in the HCI field. Particularly relevant for our study is the illusion of ownership studied through the phenomenon of the RHI and his counterpart in VR, the VHI.

The Rubber Hand Illusion in VR

The RHI phenomenon (see Introduction) has been widely studied since the late 90s. The key to achieving the illusion of ownership towards a fake arm is the visual-tactile congruency. That is when users can see the fake arm being stimulated, and they can feel the same stimulation at the same location and time on their own arm, they will be tricked to believe that the fake arm is actually their own. Following the first study by Botvinik et al. [9], many researchers investigated the key factors of this illusion. For instance, it has been demonstrated that a delay of 300 ms between the stroking of the two hands (i.e., real and fake) reduces the effect of the illusion, and a delay of 500 ms breaks the illusion [35, 71]. Kanayama et al. [37] used electroencephalography (EEG) activity in the gamma range to study the correlate of multimodal integration during the RHI using congruent and incongruent stimulation.

The advances in VR technology have made it possible to study new factors of the RHI illusion within psychology and other disciplines, including HCI [2, 31, 82]. VR technology allowed the study of additional variables of the RHI [48, 68, 72, 87]. The reproduction of the RHI in VR is defined as virtual hand illusion (VHI). The illusion is the same but is created in VR; participants wear an HMD and their arm is rendered as virtual arm. The virtual arm is shifted with respect to their physical arm. The researcher stimulates the participants' physical arm while they can see the physical stimulation through the HMD and feel it on their arm. After a while, participants will embody the virtual arm. Perez-Marcos et al. examined the results of seeing a body attached to a virtual arm [62]. Ma et al. investigated whether subjects can embody a non-corporeal object such as a virtual balloon or a square [49], and Lin et al. explored the role of graphics realism in the illusion, using different geometric hand models [44]. Choi et al. [15] studied the multisensory integration in the virtual hand illusion with active movement. Finally, Schwind et al. investigated the effect of visual realism on visual-haptic integration [70]. Successive researchers extended the VHI to the entire body [73], and studied the phenomenon of the body swap illusion (i.e., embodying another person's body)

[4, 5, 51, 59, 63, 75]. Furthermore, other studies showed that people can embody a body with a different skin color [21], a body of a different size [59], and a body of a different age [5].

Several studies explored the occurrence of the illusion for other parts of the body. For example, it has been shown that it is possible to achieve the embodiment of a fake foot (rubber foot illusion) [18, 43], and of an artificial tongue [56]. Moreover, Ramachandran et al. [65] showed that it is possible to embody a mannequin's head, and Ekroll et al. illustrated that people can be tricked into believing they have a shorter finger [20]. Finally, several researchers have demonstrated that it is possible to embody supernumerary hands [14, 28].

Taken together, these examples demonstrate how flexible our body schema is and that it is possible to perturb it to include different body parts or even an entirely different body. From an HCI perspective, these findings on the creation of bodily illusions and embodiment, provide inspiration for designing novel VR experiences involving the sense of touch, which can reinforce the embodiment. Here we explore to what extend mid-air haptics can be used to push the boundaries of the body ownership and recreate the RHI in VE.

The Use of Haptics and Mid-air Haptics

Creating convincing tactile sensations in VR is challenging, considering the complexity of the human sense of touch [7, 38]. Most prior work describes scenarios that require physical attachments, such as gloves or exoskeletons, to convey tactile sensations [6, 12, 26, 50, 57, 69]. Cumbersome tactile devices or devices which require the user to maintain a grip on them disturb the presence in the VE. Mid-air devices, which are "invisible" to the user, could overcome that challenge and help maintain the presence in the VE.

The proliferation of mid-air haptic systems that use vortexes [27], laser beams [41, 42], compressed air [76], or ultrasound waves [11, 34], open up new opportunities. These devices do not require the user to directly touch an object, or to wear an attachment such as a glove, hence creating a more immediate and unconstrained interaction in VR. While various devices are becoming available on the consumer market, mid-air haptic devices that employ focused ultrasound to deliver tactile feedback are the most promising (Fig. 2) (see Introduction). The tactile properties of ultrasound mid-air tactile devices are different from other haptic technologies (e.g., vibrotactile stimulation). They stimulate only the Pacinian corpuscles (high-frequency vibration receptors) and to a minor degree the Meissner receptors (low-frequency vibrations receptors) [84, 86]. To create tactile feedback, parameters such as frequency, intensity, duration, and direction can be manipulated to render different sensations [11]. Ultrasound haptics has a lower spatial resolution compared to physical touch (1 cm of diameter [47]). However, it still allows the creation of a multitude of sensations. For instance, Obrist et al. provided a non-arbitrary map between emotions and haptic descriptions [61], and Long et al. were able to render volumetric shapes using mid-air haptic technology [47]. Moreover, Carter et al. [11] employed ultrasound arrays as an input interface, allowing color rendering, pinch-to-zoom interaction, and the possibility of interacting with a web application. Finally Ablart et al., applied mid-air touch to enhance users' experience while they were watching short movies [1], and Vi et al. applied mid-air touch to enhance users' experience during an art exhibition [81].

Contribution of the Present Work to HCI

With our work we explore the VHI phenomenon demonstrating that our brain can fill in the gap between spatially incongruent visual-tactile stimulations (gap between what we see and what we feel on the hand) maintaining the feeling of body ownership in situation other than perfectly, spatially matching, stimulation. In particular, we exploit the advantages of an ultrasound mid-air haptic device and we recreate the VHI illusion varying the congruency of the stimulation (i.e., congruence and incongruence). We additionally employ multiple incongruent visual-tactile stimulations to overcome the effect of the current limitation of the free-hands tracking systems (i.e., imprecise spatial tracking) on reported body ownership in VR. While the VHI has been studied before, it has not been explored using the emerging mid-air touch technology (see [31] for an early paper on the RHI, but not in VR). Hence, the novelty of our study is the use of multiple mid-air tactile stimuli in VR, testing the occurrence of the VHI in congruent and incongruent conditions. This has never been attempted before but offers interesting directions because it could solve the lack of precision of free-hand tracking devices.

Following, we 1) present a first experiment in VR that exploits the VHI using multiple incongruent visual-tactile stimuli. Then, we present two additional control experiments in which we 2) assess the influence of the hand's posture when participants are stimulated with a tapping stimulation (as in our VR study) by means of physical touch, and we 3) assess the influence of the hand's posture with a stroking stimulation.

3 STUDY OF THE VHI MEDIATED BY MID-AIR TOUCH

With this experiment, we tested if the VHI can be mediated through mid-air tactile stimulation (comparing congruent and incongruent tactile stimulation) and if it is possible to maintain a sense of ownership toward a virtual arm even when using visual-tactile incongruent stimulation (multiple incongruent stimuli condition). This conditions has not been studied before, and it is interesting because it may allow the creation

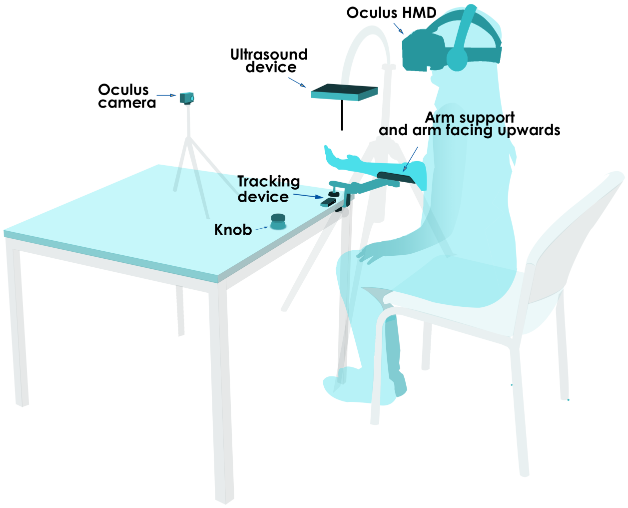

Figure 3: Set-up. The participant wore a HMD Oculus DK2 and sat on a chair with the arm resting on a support between the mid-air haptic device using ultrasound and the tracking system (Leap Motion). A knob was used to measure the proprioceptive drift.

of an illusion overcoming the limitations of the current free-hand tracking systems.

VR and Device Set-up

We used the mid-air haptic device (by Ultrahaptics) to deliver tactile feedback to the participant's real hand using stimuli modulated at 200 Hz frequency. The VE consisted of a virtual version of the space where the study took place. Fig. 3 shows the set-up with the participant resting his/her arm facing upward on an arm support. Participants received a tactile stimulation on their palm from the top, mimicking raindrops. We used raindrops as the scenario for our experiment, taking inspiration from a work by Obrist et al., where users described the sensation of the mid-air haptic device as "dry rain" [60]. This hand posture is different from the one used in the standard RHI/VHI set up, where the hand is maintained facing down. We could not use a facing down posture to experience the raindrops, as the mid-air stimulation is best perceived on the glabrous (non-hairy) part of the hand [84], and also to simulate the natural movement of a raindrop. Participants experienced a virtual arm through an HMD (Oculus Rift DK2, field of view: 100 degrees with an estimated 960 x 1080 pixels per eye resolution, displayed at 60 to 75 Hz) that was real-time tracked by a hands-free tracking device by Leap Motion. Although we did not allow for movement during our experiment, the tracking device was necessary to render the arm in VR. The virtual arm was rendered by using the Leap Motion Core Asset for Unity 3D. This package comes with the UV maps for the 3D hands allowing to match participants' gender and skin color.

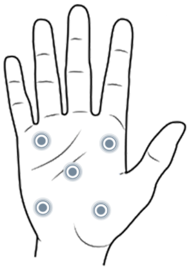

Figure 4: The five locations stimulated by the mid-air haptic device during the congruent and incongruent conditions.

Our experimental design, presented in the following sections, accounts for the difference in the set-up compared to the traditional VHI. Hence, we performed two control experiments to verify that the different hand's posture and stimulation type are not necessary for the illusion of ownership.

Study Conditions

We investigated the VHI with the two traditional conditions: 1) a congruent visual-tactile stimulation, 2) an incongruent visual-tactile stimulation, and we additionally tested 3) a multiple incongruent stimulation condition, and 4) a multiple congruent stimulation condition.

1) **Congruent condition**: stimuli in VR were rendered visually by virtual drops of water falling one after the other, with a one-second interval, onto five locations on participants' virtual right hand (see Fig. 4). The mid-air tactile stimulation on the participants' real hand matched the location seen in VR.

2) **Incongruent condition**: the tactile stimulation on the participants' real hand did not match the location seen in VR. According to previous research [9], an incongruent visual-tactile stimulation breaks the illusion. We tested this condition delivering the tactile feedback (i.e., drops of water) randomly on a different location from that which participants could see in the VE.

3) **Multiple incongruent stimuli**: this was one of the new conditions we introduced in our study. We were interested to investigate whether the illusion can also occur using multiple incongruent stimuli enabled through the mid-air haptic device. Prior work established that a minimum of 1 cm distance between mid-air focal points is needed to ensure the discriminability of two tactile points [84]. The diameter of the focal point is also approximately 1 cm, hence, we divided the hand into a 3x3 grid (see Fig. 5). We delivered different patterns of three stimuli at a time, to make sure that all of our participants could have enough surface available on the palm to receive the stimulation, and so that the perception areas

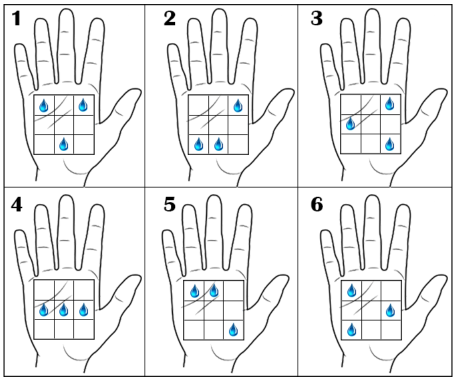

Figure 5: The six patterns used in the multiple incongruent and multiple congruent stimulation in VR. Each drop (rendered by a focal point) is approximately 1 cm of diameter, and at least 1 cm distant from the others, allowing the delivery of discrete mid-air tactile stimuli.

of the stimuli were not overlapping. Participants could see three drops of water in VR hitting the hand at the same time. The tactile stimulation on the real hand was rendered on three random incongruent locations.

4) **Multiple congruent stimuli**: as a control condition for the multiple incongruent stimulation, we also tested a multiple congruent stimuli condition. In this condition, we delivered three drops in VR visually congruent with three congruent tactile stimuli on the participant's real hand.

Overall, our investigation followed a repeated measures design with one factor at four levels (i.e., congruent, incongruent, multiple incongruent, and multiple congruent). The four conditions were randomized across participants. Ethical approval was obtained from the university ethics committee. Participants were compensated with a £5 Amazon voucher.

Measures

To investigate the VHI illusion mediated through mid-air touch we gathered two established measures: a questionnaire for the subjective feeling of the illusion, and the proprioceptive drift measurement, an objective indicator of the illusion.

The Questionnaire. We used the questionnaire originally used in Botvinick and Cohen [9] adapting the wording to take into account the difference in our set-up (e.g., the tactile stimulus was provided through drops of water in VR, rendered through mid-air tactile stimuli, instead of a brush). The questionnaire consisted of 9 items as shown in Table 1. The answers could vary on a Likert scale from 1 ("I strongly disagree") to 7 ("I strongly agree"). Q1 to Q3 measure the subjective illusion effect [9]. The remaining questions are considered as control questions.

QUESTIONS
Q1. It seemed as if I were feeling the mid-air touch in the location where I saw the drop touching my virtual hand
Q2. It seemed as though the touch I felt was caused by the drops touching the virtual hand
Q3. I felt as if the virtual hand were my hand
Q4. It felt as if my (real) hand were drifting toward the left (toward the virtual hand)
Q5. It seemed as if I might have more than one left hand or arm
Q6. It seemed as if the touch I was feeling came from somewhere between my own hand and the virtual hand
Q7. It felt as if my (real) hand were turning "virtual", less consistent
Q8. It appeared (visually) as if the virtual hand were drifting toward the right (toward my real hand)
Q9. The virtual hand began to resemble my own (real hand, in term of shape, skin tone, freckles, hairs or some other visual feature)

Table 1: The 9-item questionnaire (from [9]). We adapted the wording to take into account the difference in our set-up (e.g., the tactile stimulus was provided through drops of water in VR, rendered through mid-air tactile stimuli, instead of a brush).

Proprioceptive Drift. The proprioceptive drift is a measure to determine the relative displacement of the perceived location of one's own hand toward the location of the fake hand after the stimulation, compared with a pre-stimulation baseline. To measure the proprioceptive drift we followed a similar approach to Suzuki et al. [78]. Before and after each stimulation, participants were shown a black background in VR, with an infinite white 3D line fronto-parallel to their right hand, where a cursor (a green ball) could be moved by the rotation of a

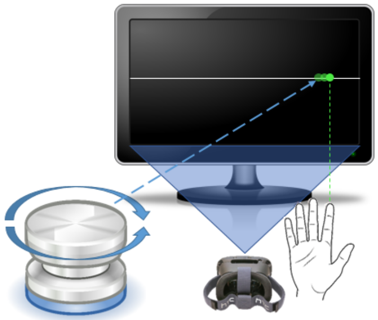

Figure 6: The proprioceptive measurement. Participants saw a black screen with an infinite white line and a cursor (green sphere) on it. By rotating the knob (left) they could move the cursor on the line until they felt the cursor position was matching their index finger.

knob (Fig. 6). Participants had to move the cursor with their left hand to match the perceived location of their index finger and press the knob to register the cursor coordinates. In all cases, the difference between the cursor's position in the pre and post-stimulation corresponded to the proprioceptive drift. A drift toward the virtual hand is considered an indicator of the illusion [9].

Participants

For this study, we recruited 20 participants (9 females). Their mean ± SD age was 25.5 ± 7.9. They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders.

Procedure

At the beginning of the study, participants sat on a chair. After putting on the HMD, participants had the possibility to explore the VE to familiarize themselves with the virtual set-up and the HMD. They were also invited to move their hand over the hand tracker system (Leap Motion), to experience the render of their hand in VR. The virtual hand was rendered but shifted about 20 cm to the left of the real hand location, to allow an appropriate mismatch for the proprioceptive drift measurement (following past procedures, see [17, 35, 52, 85]). Participants could see in VR their right arm from a first-person perspective. After this initial familiarization, the test phase started where the participants' right arm was guided onto an arm support at mid-way between the hand tracking device (Leap Motion) and the ultrasound array (see Fig. 3). The center of the participants' palm matched the center of the ultrasound array, allowing a real-time tracking of the hand. The mid-air device faced down toward the tracking device, with the subject's hand in between. The mid-air device was placed at 20 cm of distance above participants' hand, which is the optimal operative distance suggested for this device [11], and at the same time, allowed the hand tracking device to work smoothly. The chair was kept in a fixed position for every participant. In previous studies, the stimulation duration ranged from a minimum of 45 s to a maximum of 240 s [18, 19, 30, 36, 80]. As no specific explanation is provided in prior work, and given that the illusion occurred in all cases, we selected the middle value of 120 s. Participants experienced all four conditions in a randomized order (see the section Study Conditions). They were asked to focus exclusively on the palm of the hand, and to not move the right arm and hand (the one rendered in VR) to avoid receiving updated information regarding the position of their real hand. The proprioceptive drift was measured at the beginning and at the end of each condition. Additionally, at the end of each condition, participants completed the 9-item questionnaire illustrated in Table 1. The study consisted of four conditions for a total of 30 minutes. Participants wore headphones reproducing white noise to cover any environmental and device noises.

	Descriptives for Q1 + Q2 + Q3		
Condition	*Mean rank*	*Mean*	*Std. Deviation*
Congruent	2.93	5.38	1.70
Incongruent	1.84	3.75	2.05
Multiple incongruent	2.81	4.98	1.74
Multiple congruent	2.43	4.77	1.60

Table 2: Descriptives for Q1 + Q2 + Q3. The higher the values, the more ownership was felt by the participants.

Analysis and Results

Here, we present the results of the study based on the combination of the subjective (questionnaire) and the objective (proprioceptive drift) measures.

Questionnaire: All the participants completed the 9-item questionnaire four times. Q1, Q2, and Q3 were likely not following a normal distribution (Shapiro-Wilk, $p < .05$). We ran a Friedman test on the calculated means of the answers given by the participants to Q1, Q2, and Q3, for the congruent, incongruent, multiple incongruent, and multiple congruent conditions. The Friedman test indicated a significant difference between groups, $\chi^2(3) = 32.2$, $p < .001$. A Wilcoxon signed-rank test was performed to further investigate the difference between groups. We used a Bonferroni adjustment for the Wilcoxon test's results to interpret the data and avoid a type I error. Hence, we divided the significance level of .05 by the number of tests made (six). Therefore, the new significance level was set at .05/6 = .008. Descriptive statistics of Q1, Q2, and Q3 are shown in Table 2.

The congruent and the incongruent condition were significantly different, $Z = -4.69$, $p < .001$, with the congruent condition being more able to convey the illusion of ownership. There was no difference between the congruent condition and the multiple congruent and incongruent conditions ($p > .008$). In addition, there was no significant difference between the multiple congruent and the multiple incongruent conditions ($p > .008$). Lastly, our two multiple stimulation conditions significantly differed from the incongruent condition, $p < .001$. Q4 to Q9 are traditionally considered control questions. As expected, their ratings did not show any significant differences, therefore, they will not be discussed further.

Proprioceptive drift: The Shapiro-Wilk test indicated our data to likely follow a normal-like distribution ($p > .05$). In our dataset, there were no outliers. Thus, we ran an ANOVA repeated measures to compare the averages of the results (proprioceptive displacement in cm) of our four conditions.

	Cong.	Incong.	M. incong.	M. cong.
Cong.	=	≠	=	=
Incong.	≠	=	≠	≠

Table 3: Pairwise comparisons for the four conditions: congruent, incongruent, multiple incongruent, and multiple congruent. "=", no difference between groups. "≠", difference between groups.

Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(9) = 8.903$, $p = .448$. The ANOVA highlighted a statistical difference between our four conditions, $F(3,76) = 10.01$, $p < .001$. To better investigate the differences between groups, we analyzed the pairwise comparisons. Fig. 7 shows the box plot of the proprioceptive drift for the different conditions.

First, the congruent and the incongruent condition were statistically different ($p < .01$), with the congruent condition having higher scores as suggested by literature. As for the subjective feeling of ownership (questionnaire), the data for the proprioceptive drift highlighted no difference between the multiple congruent and the multiple incongruent conditions ($p > .05$). Interestingly, the congruent condition was not statistically different from the multiple incongruent ($p > .05$) and from the multiple congruent conditions ($p > .05$). The incongruent condition resulted to be statistically different from the multiple congruent condition ($p < .05$) and from the multiple incongruent condition ($p < .05$). See Table 3 for an overview of these results.

4 SUMMARY

As expected, results from the questionnaire indicated that the illusion of ownership toward the virtual arm is subjectively felt during the congruent condition. The same is true for the multiple congruent condition. However, the illusion also occurred in the multiple incongruent condition. This means that even when we deliver incongruent visual-tactile stimulation (i.e., participants see visual stimuli in one location, but they feel them on a different location) it is still possible to achieve an illusion of ownership of the virtual hand. These results are additionally confirmed by the proprioceptive measurements. Our data indicated that participants experienced the same amount of proprioceptive drift toward the virtual arm during the congruent, the multiple congruent and the multiple incongruent conditions.

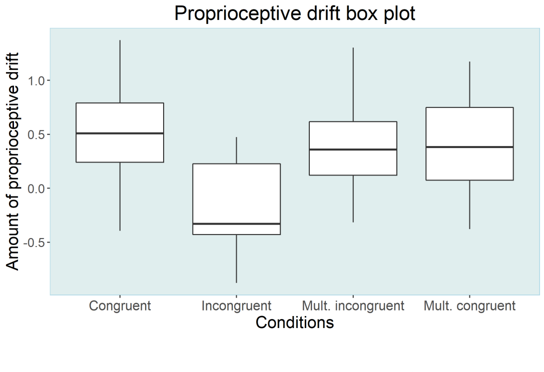

Figure 7: Box plot for the proprioceptive drift. The highest the values, the bigger the drift toward the virtual hand. In our scenario, 0.1 Unity units correspond to 1 cm.

Finally, we provide some hypotheses to justify why multiple incongruent stimuli felt as congruent. These hypothesis are: 1) Effect of temporal saliency: when the stimuli happen together we are not able to perceive the visual-tactile incongruency. 2) Spatial acuity: it decreases by increasing the number of stimuli. 3) Cognitive load: it is hard to focus the attention on the visual stimuli and their tactile effect, hence, we are not aware of the discrepancy.

Additionally, one may argue that the upward posture of the hand constricts the user to a more unnatural hand position in comparison with the downward posture. Hence, the user will receive more proprioceptive information (information regarding the position of the limbs across space) from tendons and muscles with the possible effect of reducing the strength of the illusion. Hence, we conducted two more studies (in what follows, control studies) exploiting the traditional RHI set-up, to assess the influence of the hands posture (downward vs. upward).

Effect of Hand Posture with a Tapping Stimulation

With this first control experiment we aimed to assess the influence of the hand's posture when participants were stimulated by tapping stimulation (as in our VR study) by mean of physical touch.

Conditions. We delivered tactile stimulation through two paint brushes (simulating the raindrop sensation in our mid-air stimulation in VR) with a diameter of 1 cm at the tip. The physical tactile stimulation was delivered on the real and on the rubber arm. The study was composed of four randomized conditions:

(1) Palm down and synchronous stimulation.
(2) Palm down and asynchronous stimulation.
(3) Palm up and synchronous stimulation.
(4) Palm up and asynchronous stimulation.

During each condition, the rubber hand was at a distance of 20 cm from the participant's hand. The stimulation was a tapping-like (non-continuous) stimulation lasting 120 seconds. The experiment lasted 30 min and participants received £5 Amazon voucher.

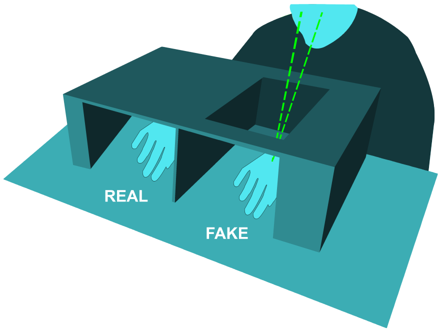

Figure 8: The RHI set-up. A cardboard box was built. The box had two entrances, one for the participant's right arm, and one for the fake arm. Once inside the structure, participants could see only the fake arm.

Participants. For this control experiment, we recruited 10 new participants (5 females). Their mean ± SD age was 21.8 ± 1. They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders.

Measures and Procedure. The behavioral measures obtained were the same as in our previous study: the questionnaire and the proprioceptive drift. We measured the proprioceptive drift before and after each condition. To do that, we built a cardboard box that had two entrances (see Fig. 8). The right entrance was for the participant's right arm; once in it, they were not able to see their real arm. The rubber arm was introduced in the left entrance. Furthermore, participants' right shoulder was covered with a black cloth. Before and after each condition, we asked participants to close their eyes and to mark over the cardboard box where they thought the position of their right index finger was. For a more accurate measurement, they repeated this process six times for each condition, three times before the stimulation, and three times after the stimulation. We calculated the averages of the three measurements before the stimulation and of the three after the stimulation. The difference between the averages of the pre- and post-stimulation was then used to assess the proprioceptive drift (in cm). As before, after each stimulation participants were asked to complete the 9-item questionnaire (see Table 1).

Analysis and Results. Questionnaire: All the participants completed the 9-item questionnaire four times. Our data did not follow a normal-like distribution, therefore we proceeded with a Friedman test on the grouped Q1, Q2, and Q3, of our four conditions: palm down synchronous, palm down asynchronous, palm up synchronous, and palm up asynchronous. The Friedman test indicated a significant difference between groups, $\chi^2(3) = 38.8$, $p < .000$. A Wilcoxon signed-rank test was performed to further investigate the difference between groups. We employed a Bonferroni adjustment on the Wilcoxon tests results, in order to avoid a type I error. Hence, we divided the significance level of .05 by the number of tests made (six). Therefore, the new significance level was set at .05/6 = .008. Data showed a significant difference between the palm down synchronous vs. palm down asynchronous condition, Z = -3.67, p < .001. There was also a significant difference between the results for the palm up synchronous vs. the palm up asynchronous condition, Z =-4.01, p < .000. A comparison between the palm down synchronous and the palm up synchronous condition did not highlight any difference (p = .574). Descriptive statistics for Q1, Q2, and Q3 are shown in Table 4.

	Descriptives for Q1 + Q2 + Q3		
Condition	*Mean rank*	*Mean*	*Std. Deviation*
Palm down sync	3.25	4.83	1.64
Palm down async	2.13	3.20	1.44
Palm up sync	3.05	4.67	1.86
Palm up async	1.57	2.57	1.13

Table 4: Descriptives for Q1 + Q2 + Q3. The higher the values, the more ownership (occurrence of the illusion) was felt by the participants.

Proprioceptive drift: We first checked the proprioceptive drift data for normality. The Shapiro-Wilk test indicated a normal-like distribution (p > .05). Thus, we ran a two-way repeated measures ANOVA to compare the averages of the results of the four conditions. While we found a significant difference between the synchronous and asynchronous conditions (p = .013), as expected we did not find a significant difference between the palm's postures (p = .73).

This first control experiment demonstrated that the hands' posture is not crucial to ensure a successful embodiment of the fake arm. Hence, our study results using the upward posture in the mid-air haptics VHI set-up are strengthened. In the next control experiment, we again tested the hands' posture, this time using a stroking-like tactile stimulation (as in the traditional RHI/VHI set-up).

Effect of Hand Posture with a Stroking Stimulation

We now test the hands' posture with a stroking stimulation.

Conditions. This experiment was structured identically to the previous control experiment, however, instead of a tapping stimulation, we stimulated the real and the rubber hand with a stroking (continuous) stimulation.

Participants. For this experiment, we recruited a new set of 10 participants (6 females). Their mean ± SD age was 22.3 ± 1.4. They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders.

Measures and Procedure. The behavioral measures were the same as in the previous control experiment: the 9-item questionnaire and the proprioceptive drift measurement.

Analysis and Results. Questionnaire: All the participants completed the 9-item questionnaire four times. The resulting data did not follow a normal distribution, therefore we proceeded with a Friedman test on Q1, Q2 and Q3 of the four conditions: palm down synchronous, palm down asynchronous, palm up synchronous, and palm up asynchronous. The Friedman test indicated a significant difference between groups, $\chi^2(3) = 52.9$, $p < .000$. A Wilcoxon signed-rank test was performed to further investigate the difference between groups. We applied a Bonferroni adjustment to the Wilcoxon tests results, in order to avoid a type I error. Hence, we divided the significance level of 0.05 by the number of tests made (six). Therefore, the new significance level was set at .05/6 = .008. Data showed a significant difference between the palm down synchronous vs. asynchronous condition, Z = -4.38, p < .000. We found the same result for the palm up synchronous vs. asynchronous condition, Z =-4.32, p < .000. A comparison between the palm up vs. palm down synchronous conditions did not highlight any significant difference (p = .284). Descriptive statistics for Q1, Q2, and Q3 are presented in Table 5.

	Descriptives for Q1 + Q2 + Q3		
Condition	*Mean rank*	*Mean*	*Std. Deviation*
Palm down sync	3.38	6.10	1.39
Palm down async	1.75	3.10	1.66
Palm up sync	3.20	5.93	1.59
Palm up async	1.67	3.33	1.90

Table 5: Descriptives for Q1 + Q2 + Q3. The highest the values, the more ownership was felt by the participants.

Proprioceptive drift: We checked the proprioceptive drifts data for normality. The Shapiro-Wilk test indicated a normal-like distribution (p > .05). Thus, we ran a two-way repeated measures ANOVA to compare the averages of the results of the four conditions. We found a significant difference between the synchronous and asynchronous conditions (p = .025). There was no difference between the palm's postures (p = .31).

This second control experiment re-confirmed that the hands' posture is not affecting the RHI, even when we use a stroking-like stimulation. Thus our findings using mid-air tactile stimulation in VR are strengthened.

Effect of Stimulation Type

In the previous sections, we showed that the traditional hand posture is not a determinant factor for the success of the RHI. Participants will have an equal sense of ownership toward the virtual arm regardless of their hands' posture. Once we clarified that the hand posture is not a crucial factor for the illusion of ownership, one may argue that the stimulation type (continuous or non-continuous) can have an impact on the illusion. Particularly, seen that we use a tapping stimulation (non-continuous) in our VR experiment, which provides less tactile information, this might have reduced the desired effect. In this section, we will compare results from the two control experiments to assess the importance of the stimulation technique.

From a first exploration of the data our sample seemed likely to follow a normal distribution, as indicated by the histograms and the Shapiro-Wilk test (p > .05). No outliers were found. We proceeded with an independent sample t-test. we compared the four different conditions (palm up synchronous, palm down synchronous, palm up asynchronous, palm down asynchronous) divided by the two stimulation types (tapping and stroking). All of the four tests showed a non-significant difference between the four conditions when taking into account the stimulation type (p > .05). This means that the stimulation type is not a crucial factor for the success of the illusion of ownership.

In conclusion, the results of these two control experiments show that the hand posture and the stimulation approach do not affect the occurrence of the illusion of the RHI. Thus, we can disregard those two factors as confounding factors in our study in VR using mid-air touch to create an illusion of ownership (VHI). This strengthens our results with respect to the new finding of creating an illusion using incongruent multiple stimuli. In the following section we will discuss the implications for future design explorations.

5 DISCUSSION

Our main experiment in VR demonstrated how multiple visual-tactile incongruent stimulations were perceived as a congruent experience by the user. This can contribute to the design of even more realistic and immersive experiences in VR. Below we provide a final discussion on the findings and their relevance for HCI.

VHI Mediated Through Mid-Air Touch

We investigated the virtual hand illusion introducing five variants to the traditional paradigm. Such variants regarded 1) the posture of the hand (palm upward vs. downward), 2) the stimulation type (tapping vs. stroking), 3) the number of incongruent stimuli delivered simultaneously during the stimulation (in the condition where multiple spatially incongruous/congruous taps were delivered to the virtual hand), 4) the use of a mid-air haptic device to deliver the tactile feedback. Our results indicated a subjective feeling of ownership toward the virtual arm during spatially congruent visual-tactile stimulation (see [9]),regardless of the number of the stimuli delivered simultaneously on the hand. Interesting, multiple spatially incongruent stimuli were also able to induce feeling of ownership in the users. In other words, it is possible to elicit body ownership toward a virtual arm even when there is a gap between what we see in VR and what we feel in reality, as long as the stimulation happens in multiple location simultaneously.

To test the influence of the new variants which we introduced in our set-up compared to the traditional RHI/VHI, we performed two additional control experiments, accounting for two different hand postures (upward vs. downward) and two different stimulation type (tapping vs. stroking). The results from the subjective reports and from the objective measurement did not highlight any influence of hand posture or stimulation type on the occurrence of the illusion, which took place as described in literature in cases where the palm was facing downward and the tactile stimulation was delivered by stroking.

Design Potential Around Multiple Incongruent Stimulation

We envision three design scenarios that exemplify the benefit from the visual-tactile incongruence stimulation and highlight potentials for future research

Scenario 1: We can imagine an AR/VR interface (e.g., computer desktop) where the user can select the icons receiving tactile feedback. The free-hand tracking system does not allow a precise matching between the visual and the tactile cues. Therefore, when touching the edges of the virtual icons on the interface, one could receive the tactile feedback on the wrong location on the hands with respect to what he is looking at in the VR/AR environment. This is a situation where multiple incongruent tactile points (the edges of the virtual icons' shape) are displayed visually in a certain location but rendered tactilely on a different one. Nevertheless, our design could provide a solution, since that users would be able to feel the multiple incongruent stimulation as congruent. In this way, we can provide the user with an understandable and realistic tactile percept, even in an incongruent visual-tactile stimulation. We still do not know if our paradigm could be applied on the fingertips; future research needs to investigate tactile perception of multiple incongruent stimulation on the fingertips in which the density of tactile receptors varies.

Scenario 2: Similarly, our paradigm could be applied to those applications where the system (e.g., VR or AR) would need to render a perfect reproduction of the real environment to allow physical social interaction. For instance, one of the last VR social networks, Facebook Spaces, shows how multiple people from different locations can join together in a shared virtual space. Each of the users is represented in the VE through an avatar simulating their body presence. These avatars are obviously different in shape from the bodies of the users. This means we do not have a one to one representation of the users' body. In other words, if one of the users in the VE would like to express something via touch to another virtual user, both of the users will have to deal with a non-perfect visual-tactile correspondence. Our study indicates that even if the users A and B will see the tactile stimulus happening on a certain spot (on the virtual avatar) and they will feel it on another (on their real body), the experience will be perceived as congruent. Future work can expand this knowledge towards an exploration of multiple incongruent stimulation at different body parts (e.g., fingertips, shoulders, torso, etc.).

Scenario 3: In the famous movie "Singing in the rain", Gene Kelly is dancing and singing in the rain. What few know, is that after that scene, Gene endured a 103 F (39° Celsius) fever. Based on our work, we can imagine people watching this movie scene in a cinema or home cinema setting, feeling the sensation of being under the rain, without getting wet or sick. In fact, mid-air haptics can provide the sensation of "dry rain" [60]. For such complex scenario, further insights into the tactile perception of mid-air haptics and the creation of illusions is required. However, as shown by prior work (see [1]), there is the potential to design more immersive and emotionally engaging movie experiences through the use of mid-air haptic technology.

In summary, all the three design scenarios will benefit from the "invisibility" of the mid-air haptic device, which provides attachment-free interactions strengthening the immersion in the fictional environment (see [22]). Furthermore, we can imagine a wall consisting of ultrasonic arrays that will surround the user providing a 360° free-hands multiuser interaction room that will deliver tactile stimulation as desired without the user being aware of the stimulation medium. In this way, the tactile stimulation could follow the natural movement of the user and allow scalability beyond the user's hands.

Limitations and Future Works

Although this work presents a first of its kind investigation into the use of mid-air tactile stimulation to investigate the occurrence of body ownership during a visual-tactile incongruence, we also need to acknowledge some limitations.

While the technology opens up new possibilities for HCI designers, the range of perceivability of the tactile stimulus on the body is still limited, following the Pacinian mechanoreceptors distribution on the body. We focused our research on the hand but the occurrence of the illusion at other parts of the body still remains to be explored, once the technical limitations will be overcome. Regarding the optimal operative distance from the skin (15 cm), different researchers are looking for ways to extend the performance of transducer arrays. One promising way is the use of acoustic meta-materials: classic materials (like paper, plastic, wood) micro-engineered to have specific acoustic properties, that have already been used in combination with the device employed in this paper [55]. Moreover, our design could be tested with other mid-air devices. This will help in establishing a solid foundation for creating full-body immersive experiences in VR.

We started the investigation of the visual-tactile incongruency using three stimuli on the hand to make a clean setup and a first exploration of the VHI with multiple incongruent visual-tactile mid-air stimulation. Future work could explore further the phenomenon of the VHI using a different number of stimuli to establish a model of our perception under visual-tactile incongruency. Although in this case, one would have to keep in mind the nature of the mid-air tactile stimulation, which has a lower and not precisely defined spatial resolution compared to physical touch (e.g., the mid-air focal point is maximally perceived at the center of its focus, and less on the boundaries).

Finally, it would also be interesting to study the time variable, investigating if it is possible to achieve the same results with time asynchrony. Moreover, in our set-up, we used the mid-air technology statically, under controlled variables, with less confounding variables. Future studies could investigate similar effects while users are free to move across space.

6 CONCLUSIONS

In this paper, we illustrated that users can perceive an incongruent visual-tactile stimulation as congruent. The findings from our experiment in VR demonstrate for the first time that it is possible to elicit the VHI by means of multiple visual-tactile incongruent stimulation using mid-air haptic technology. We accounted for the new variables introduced in our set-up with two additional control experiments, adding knowledge to the phenomenon of the VHI. Our research helps to replicate and recreate realistic tactile sensations in VR, that can occur also when having a visual-tactile incongruency. This is particularly relevant as long as tracking systems are not optimal to precisely locate users' hands' position in real-time [3, 13, 24]. Hence, understanding if our brain can fill the gap between what we see and where we feel it will be useful for designing more immersive scenarios in VEs. These findings will be useful to design more compelling and immersive scenarios in multimedia technology such as movie theaters, home cinemas, and VR interactions. Future extensions and explorations can now commence to integrate a more realistic tactile feedback in VR/AR interfaces, VR applications and movies.

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