Inducing Body-Transfer Illusions in VR by Providing Brief Phases of Visual-Tactile Stimulation

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ABSTRACT

Current developments in the area of virtual reality (VR) allow numerous users to experience immersive virtual environments (VEs) in a broad range of application fields. In the same way, some research has shown novel advances in wearable devices to provide vibrotactile feedback which can be combined with low-cost technology for hand tracking and gestures recognition. The combination of these technologies can be used to investigate interesting psychological illusions. For instance, body-transfer illusions, such as the rubber-hand illusion or elongated-arm illusion, have shown that it is possible to give a person the persistent illusion of body transfer after only brief phases of synchronized visual-haptic stimulation.

The motivation of this paper is to induce such perceptual illusions by combining VR, vibrotactile and tracking technologies, offering an interesting way to create new spatial interaction experiences centered on the senses of sight and touch. We present a technology framework that includes a pair of self-made gloves featuring vibrotactile feedback that can be synchronized with audio-visual stimulation in order to reproduce body-transfer illusions in VR. We present in detail the implementation of the framework and show that the proposed technology setup is able to induce the elongated-arm illusion providing automatic tactile stimuli, instead of the traditional approach based on manually synchronized stimulation.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces–Input Devices and Strategies, Evaluation / Methodology; I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism–Virtual Reality

Keywords

Vibrotactile feedback; body-transfer illusions; 3D touch interaction; virtual environments; head-mounted display

1. INTRODUCTION

Most traditional immersive virtual environments (IVEs) are focused solely on the visual and auditory modalities, which often limits the user's sense of body ownership and embodiment in virtual environments. However, by combining IVEs composed of head-mounted displays (HMDs) with head, hand and body tracking, with haptic feedback devices enables the creation of interactive experiences providing embodied visual, auditory and haptic feedback in response to user actions. In this way, it is possible to reproduce perceptual illusions involving tactile sensations, in which the stimulation of the sense of touch can be provided with an actuated device instead of using a real object, extending the interaction possibilities of the user, creating compelling illusions and, for instance, even creating the sense of having bigger, shorter or elongated limbs [1, 16, 31]. Additionally, current technology provides low-energy, wearable and wireless components to create ergonomic and low-latency vibrotactile devices, reliable enough to automate the creation of perceptual illusions in IVEs and possibly inducing effects similar to real-world demonstrators.

In this paper, we propose an approach to reproduce perceptual illusions, involving a hand-worn haptic device and an IVE with hand tracking to provide visually synchronized vibrotactile feedback on the fingers and the palm surface, offering freedom of movements and comfort for common hand-interaction tasks. Using the developed haptic gloves we show that we can reproduce a body-transfer illusion with brief phases of visual-tactile stimulation, thus offering an interesting way to create new spatial interaction experiences in virtual reality (VR). An implemented use case showed visual-motor and visual-tactile correlations in a perceptual experiment within a VR scenario, providing sight-and-touch sensory inputs in order to reproduce the illusion of an elongated arm.

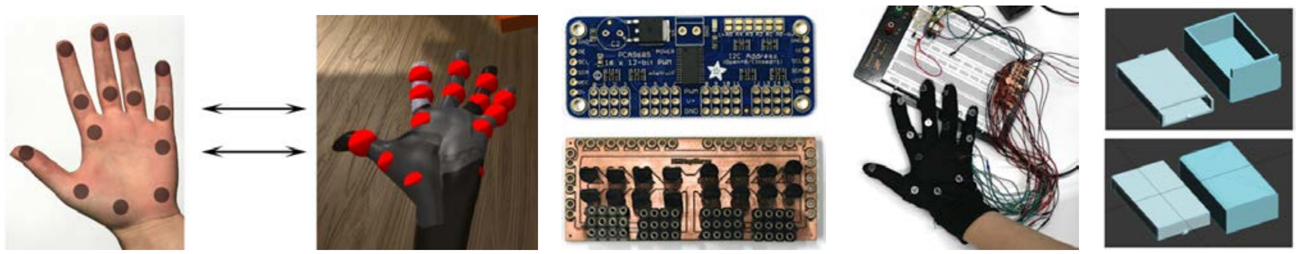
2. RELATED WORK

In this section we summarize previous work related to vibrotactile devices and perceptual illusions.

2.1 Vibrotactile Devices

This work builds on research focused on wearable devices offering tactile sensations on the hand through on-skin vibrotactile stimuli eliciting the Panician Corpuscle receptors. Related research includes the work of Kramer et al. [17] involving prototypes of haptic hand-worn devices comprising vibrating actuators and bending sensors to test the effects of intensity and length of activation on the feeling of objects. Muramatsu et al. [21] developed a glove with vibration motors for perception experiments. More recent work, proposed vibrotactile gloves providing tactile sensations in order to evaluate texture discrimination [19] and shape recognition [9]. Martinez et al. [20] also developed a glove with 12 vibrators and optical tracking based on infrared LED markers. Other approaches are based on vibrotactile displays providing navigation cues in computer-aided surgery systems [12] and assistance in tele-

ACM ISBN 0. . . 0
DOI: 0



(a) (b) (c) (d)

Figure 1: Arrangement and components of the vibrotactile display:(a) Distribution of the vibration actuators on the hand, (b) the PWM signal controller, (c) electronics testbed and (d) 3D-printed case.

operated assembly processes [7]. In contrast, recent research also based on haptic gloves [13] uses electro-tactile displays instead of vibration actuators to provide tactile feedback on grasping tasks in a VR environment, and other studies are focused on cutaneous and kinesthetic feedback with active thimbles [27].

The mentioned contributions and their foundations provide assessments and insights that are useful to design and create hand-worn vibrotactile devices which can be used on IVEs to facilitate the reproduction of body-transfer illusions. Our proposal integrated those insights to offer a wireless, low latency hand-worn pair of gloves, using materials to facilitate hand tracking with low-cost equipment, i. e. Leap Motion, and featuring easy integration with the graphics software in order to accurately activate the vibrotactile actuators when collisions are detected. In addition, our device architecture could be easily scaled to cover bigger body areas, enabling the creation of more complex vibrotactile wearables without a significant decrease on the current performance or latency.

2.2 Perceptual Illusions

Well-known perceptual illusions like the rubber-hand illusion, aiming to induce in the participant the sense of being touched on a fake arm behaving as if it would be part of their body [4] and the elongated-arm illusion [16], aiming to extend the body space by means of elongated virtual limbs, as well as the neural mechanisms which are responsible for perceptual illusions, in particular, the integration of tactile and visual feedback, are well-studied [6, 8, 10]. There have been discussions in the literature about how the fake limb should look like, in comparison with the real one. Prior research claims that there must be some correlation between the fake arm and the real one [31]. Newer investigations show that the illusion can be reproduced in VR and, in addition, it does not appear important whether the fake arm has the correct skin color or garments as the participant's arm and the illusion effect can even be achieved under controlled distortions between proprioceptive and visual information. However, the effect is negated when an abstract representation of the arm (such as an arrow) is displayed [33].

Further research shows that a perceptual illusion of body swapping can be induced for the whole body with an HMD showing stereoscopic real-time video imagery [22]. Investigations in HMD-based immersive virtual environments argued that a virtual body is a critical component and that it has a major effect on the users [11, 25], even for embodiment in body-representation illusions [29]. In investigations by Slater et al. [26] participants showed a higher sense of presence by using their virtual body to touch than by those who just pressed a button to confirm actions during experiments.

However, so far there are no conclusive results about the effects of replacing the traditional approach to provide the tactile feedback i. e. manual and synchronized tapping, with automatic vibrotactile stimuli using a wearable device. Our proposed framework offer automatic stimuli in response to user interactions within the IVE, enabling the induction of body-transfer illusions without movement restrictions caused by tapping mechanisms or operators providing the tactile feedback.

3. VIBROTACTILE GLOVE DEVICE

We designed our device as a glove to recreate the sense of touch with vibrotactile feedback while the user is exposed to a VR visual stimulus involving body-transfer illusions. In this section, we detail the concepts and the implementation details of a pair of tactile devices (for bimanual interaction), which offer a wireless, lightweight and responsive tactile display solution, able to provide synchronized visual-tactile stimuli in VEs.

3.1 Vibrotactile Display

There is a wide range of methods to provide tactile feedback (i. e. temperature, vibration, pressure). Our approach is based on coin-type linear resonant actuators (LRAs), used to create vibrations by powering a voice coil, which moves a magnetic mass and vibrating at a resonant frequency in one dimension; in this case, the normal direction to the hand's palm surface.

The proposed glove consists of 14 PMC10-100 LRAs[1] distributed over the hand (see Figure 1a). The quantity of actuators was defined as a balance between device mobility and power usage while still offering a comfortable wearable device. The positions were chosen regarding neurological aspects; the density of actuators on individual parts of the hand depends on the size of the area in the somatosensory cortex. We concentrated on the fast adapting Pacini corpuscles (PC) described by Stark et al. [30] in the fingers and palm of the hand. The receptors are primarily reacting to vibration so it is easy to stimulate them with LRA actuators [5, 18]. The receptive fields of cortical neurons on the fingertips are smaller than the one on the palm. Therefore, each finger has two actuators, which are placed on the fingertip and above the metacarpophalangeal joints. The palm has only four actuators: Two on the ball of hand and two on the palmar surface, renouncing on placing one vibration motor in the middle of the palm, as it could not touch the skin under certain hand postures [9]. Israr and Poupyrev [14] proved with their tactile brush algorithm, that it is possible to create continuous, high-resolution tactile stimuli with a low-resolution grid of vibrating actuators by using the apparent motion and the phantom illusion.

For the resonance frequency Kuroki et al. chose 240 Hz for their mechanical feedback to stimulate the PC [18]. In general PC stimulate in an interval of 10 -500 Hz with a minimal threshold of 150-

[1]http://www.precisionmicrodrives.com/

300 Hz [5]. If the frequency is high, the localization of the single signal gets more difficult because the stimuli are propagated. After a test to detect stimuli overlapping, we set a frequency of 175 ± 5 Hz so the vibration is not too strong for sensitive people and keeping the source still distinguishable.

As a result, our grid of actuators can stimulate the hand in a detailed manner that is enough to provide the touch sensations required in perceptual illusions experiments, emitting vibration stimuli between the acceptable range [18]. The vibration motors are attached with a rubber band to a thin fabric glove. Previous prototypes of our device have shown that normal gloves do not create enough tension to produce the same vibration on different hand sizes. With regards to Choi and Kuchenbecker we included rubber bands to “ensure signal transmission” [5] and that the motors are nearly on constant places for a wide range of hand sizes.

3.2 Device Controller

The actuators are controlled by an Adafruit 16-channel 12-bit pulse width modulation (PWM) driver[2] and are powered by a 3.7V lithium polymer ion (LiPo) rechargeable battery. A self-made circuit board organizes the connections, provides signal enhancements (including amplifying, basic active breaking and basic overdriving) and fits directly onto the PWM driver (see Figure 1b). The driver is connected to an ARM Cortex System on a Chip (SoC)[3] via I2C. In addition, the SoC features Bluetooth Low Energy (BLE), which enables the wireless communication between the computer and the haptic gloves, decoupling the client PC which runs an UDP server sending activation commands to the vibrators according to the user actions. This UDP server is a standalone middleware that handles the BLE transmission of data to the gloves (See Figure 5). On the server side, low level BLE connections control the gloves independently, in this way was possible to optimize the data transmission, matching the processing threads with the wireless connections. To mount the circuitry around the arm, all the components are installed in a 3D printed case, which is attached to a neoprene arm belt (see Figure 2). The case also contains USB chargers for ease battery recharging and its dimensions are 108mm $\times$ 80mm $\times$ 39mm (see Figure 1d). The case is meant to be worn on the forearm, close to the elbow, pointing outside to keep the arms able to rest and interact freely in the personal space.

3.3 Tactile Control Points

When emitting signals to the vibration motors, we address the motor independently with values to define the intensity of vibration. Before emitting signals, we have to determine the intensity for each vibration motor. We do this by attaching Tactile Control Points (TCPs) to the avatar’s hand bones at specific locations, which represent the real vibrators’ locations on the gloves. Instead of using full vibration intensity when in contact with a surface, following an on-off approach, TCPs inherit an intensity value dependent on their distance to the nearest touchable collider in the scene. The used distance function is defined by $(1 - x/0.01)^4$ and returns values greater than zero for distances between zero and one centimeter, as shown in Figure 3. The “actual distance" refers to the size of the depicted hand, while the graph is only valid for the examined point on the surface at the coordinate (0,0). After determining the intensity for each TCP, all the data is collected and sorted by a central organizer unit. This unit puts all the intensities into an encoded-data packet and sends it to the UDP server (See Figure 5).

[2]https://www.adafruit.com/product/815

[3]https://www.nordicsemi.com/products/nRF51822

The choice to emit an intensity based on distance rather than contact, stems from the way the tracked hands interact with virtual objects. It is because of our inability to detain the user’s real hands from moving when the correspondent virtual hands should, due to collisions. If we stopped the virtual hands from moving further in a direction because of an obstacle, we could not synchronize this behavior to the user’s real hands, which are free to move in any direction at any time in our setup. Since it is a delicate task to maintain a hand position that actually provides tactile feedback while touching a static surface, we defined a certain range around the surface that would trigger a vibration on our glove. This eventually led to the implementation of the distance function to provide a more elaborate sensation.

Figure 2: Images of (top) self-made glove with the electronic case attached to the forearm, and (bottom) participant interacting with the VR application, wearing the pair of gloves and the Oculus Rift DK2 with the Leap Motion attached in front to facilitate the hand tracking.

3.4 Device Latency

The glove’s latency between the UDP server and the vibration actuators was measured with a high-speed camera at 240 frames per second. Each frame was analyzed to determine the time the signal was sent and the time the vibration actuators started swinging. The calculated latency is 25ms ± 4.166, which is near the “impact threshold" defined by Jay et al. [15]. This means the user’s performance may decrease slightly, but the user stays unaware of the latency. The user would start noticing the latency when the system’s latency exceeded the “perception threshold" at 50ms. There was no measurable difference in latency between driving one motor

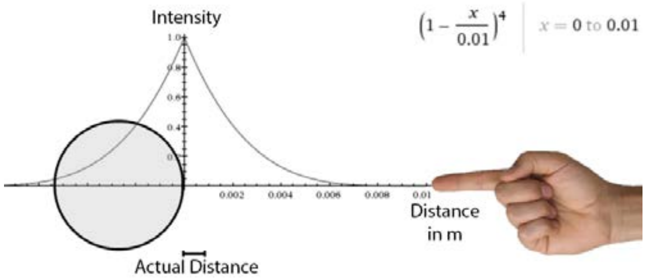


Figure 3: Curve depicting the signal to activate the vibrators and provide vibrotactile feedback as a function of the distance between the hand' representation and the virtual object.

and driving all motors at once because of the buffering settings in our embedded code and our multi-threaded approach on the client side. The presented value should be added to the latency between the hand tracking system and the UDP server to get the end-to-end latency, which makes a total of 43ms, which is still compatible with users' tolerance between sensations corresponding to visual and tactile modalities [24].

3.5 Integration

We integrated the vibrotactile glove into a VR setup using the Unity3D engine and an Oculus Rift DK2 head-mounted display with a Leap motion controller for hand tracking. The tracked pose of the glove can be used to induce vibrotactile feedback, for example, when collisions with virtual objects are detected. All the interaction between the VR software/hardware, the device controller and the vibrotactile device can be depicted in Figure 5.

4. EXPERIMENT

In this section we describe the within-subject experiment conducted to analyze whether the vibrotactile feedback condition, using our proposed device, can reach a similar effect strength as the traditional reference condition, in which tactile stimulation is applied manually with a real-world object as commonly used to induce the elongated-arm illusion in psychological experiments.

4.1 Setup

The virtual environment was designed with the Unity3D engine and deployed on an Intel computer with a Core i7 hexacore at 3.5 GHz CPU with 32 GB RAM and two Nvidia GeForce GTX 980 graphics cards in an SLI array. We used an Oculus Rift DK2 as a fully immersive display and a Leap Motion for hand tracking. In order to guarantee a reliable hand tracking for rested-forearm tasks and according to our experiences, the Leap Motion was tilted down by approximately 13 degrees using a 3D printed mount. Also, noise cancelling headphones were used to increase the immersion and filter out background noises.

As we wanted to make the experience as little irritating for the participants as possible, we chose to create a neutral environment in which a participant's avatar is seated in a desktop setup, looking from the avatar's point of view. This scene recreates the actual constellation of the participant to the chair, table and screen in the physical experimental setup. We ensured that sufficient free space was available between the participant and the screen in order to let them interact with their hands with virtual objects or interfaces 4.

A simple 3D user interface was included so that the participants could advance through the different experimental steps at their own pace. This was carried out via two hand panels, hovering above the table, which could be touched simultaneously to indicate that the participant was ready to be given the next instruction. The virtual room was refined by adding details in the form of furniture, windows, plants and decorative assets to reproduce the impression of the real place uses for the study.

4.2 Tasks

The experiment consisted of three phases. The first phase introduced the participant to the sensation of the vibrotactile feedback. This included being exposed to visual-haptic stimuli on the hands and recognizing basic shapes like a cube or a sphere. In the second phase, the participant's arm was stabilized in a comfortable position on a wedge of foam, and the participant was asked to hold the physical arm still while concentrating on the virtual arm, which was slowly elongated and after reaching twice-and-a-half of its original length was slowly retracted again to its normal length. While doing so, a virtual ball was bouncing on the virtual hand to attract the attention of the participant. The sensation of touch provided by the bouncing ball was assigned randomly and produced according to our two experiment conditions:

1. Through vibrotactile feedback activating the vibrating actuators in the gloves according to the collisions detected between the virtual hand and the virtual bouncing ball (further called *Vibrotactile Condition*).

2. Through a real ball which was bounced synchronously on the participant's real hand by a member of the team, tapping gently the real hand of the participant every time the virtual hand was touched by the virtual bouncing ball (further called *Tapping Condition*).

Once the second phase was finished, the participant was asked to answer a survey regarding the feeling and sensation of having an elongated arm. Also, the participant had to estimate the length of the perceived elongated arm. For the third phase, the participant had to repeat the same procedure as in phase two, but received feedback according to the remaining condition. Again the arm was elongated, but in contrast to phase two, it was threatened with a sudden event occurring when it was fully elongated, which consisted of a heavy object falling from the ceiling. Finally, the fourth phase gathered the same subjective data as the second phase.

4.3 Participants

In a time span of two weeks, 37 participants were recruited through academic mailing lists to test the experiment. All of them gave their informed consent and the study was approved by and conducted in accordance with the local Ethics Committee. The variety of age was between 10 and 54 years old ($M = 28.0$, $SD = 9.1$). The aspect of gender was distributed with 26 male and 11 female participants, mostly computer science students and IT professionals and all of them had normal or corrected vision. Two-thirds of the participants reported no prior experience with experiments involving vibrotactile devices. The mean time per subject, including questionnaires and instructions, was about fifty minutes. After removing a participant who failed the stereoscopic vision test, the analysis employed data of 36 remaining participants.

4.4 Procedure

The participation started with a demographic questionnaire and the Titmus test [28] for stereo-blindness assessment. The participants sat on a static chair in front of a table. Two computers were used for this experiment. The first one was only used for the testing environment and measuring the interpupillary distance (IPD). The

(a) (b)

Figure 4: Virtual environment and visual stimuli: (a) Virtual room simulating the real-world environment of the experiment, and (b) view of the 3D user interface used to navigate through the experiment tasks.

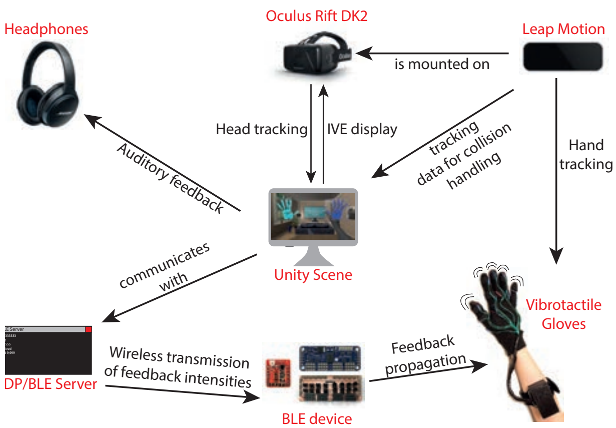


Figure 5: Interaction between the software and hardware components.

Variable	p-value	r	Z
Ownership	0.037	0.247	-2.094
Proprioception	0.007	0.348	-2.653
Comfort	0.300	0.127	-1.078
Variable	**p-value**	**Cohen's d**	**t(df)**
Perceived Length	0.043	0.350	t(35)=-2.101

Table 1: Results for the significance tests.

monitor was needed to synchronize the stimulation with the real ball at phases two and three. Unused devices (including keyboard, mouse, connector etc.) were moved away to not be a hindrance to the participant during the experiment. The second computer was used only for answering questionnaires. The table was covered with an infrared light absorbing material to support the tracking of the Leap Motion. For the experiment itself, the participants were asked to wear multiple devices: The Oculus Rift DK2 HMD with the attached Leap Motion sensor, the noise-cancelling headphones and the pair of HapGloves (see Figure 2).

For the stimulation with the real ball, a matching-size sphere was glued to a stick, so the member of the research team would not touch and distract the participant. In order to achieve higher accuracy in the *Tapping Condition*, the same experimenter performed all the tapping actions during the whole experiment. In addition, training sessions were conducted apriori to reduce the variance on timing and intensity, thus achieving a synchronous and believable movement comparable to the *Vibrotactile Condition* that consistently matches the visual feedback.

During and after the experiment, the results were collected in three different ways. First, a questionnaire was answered by the participant. As a second result, an attending member of the research team subjectively evaluated the reaction to the sudden event of a heavy object falling from the ceiling on a scale from 0 to 10 (being 10 the highest score), according to reflex reactions of the participant's body avoiding the threat and offering insights about the achieved sense of body ownership. To avoid experimenter bias, the evaluation was quantified according to predefined guidelines to score reactions like going back with their head and arms, twitching, faster breathing or comments made by the participants. Lastly, the participants were asked to judge their own feeling and reaction towards having his arm elongated and threatened by the sudden event. Directly after the elongated-arm stimuli (phase two and three), the participants were asked to answer different questions regarding their feeling of ownership of the virtual arm (scale 0 to 10 for the first three questions):

1. Please judge your sense of having an elongated arm.
2. Did the elongated arm feel like a part of your body?
3. How comfortable did you feel with an elongated arm?
4. How long do you think your elongated arm was (in %)?
5. Additional comments (I liked..., I didn't..., because...)

The four dependent variables, defined as *Ownership*, *Proprioception*, *Comfort* and *Perceived Length* from the first four questions, focus on the feeling of body ownership. If the corresponding answers show a trend towards high values, we can conclude that the elongated-arm illusion could be correctly induced [16]. The additional comments were used to comprehend and confirm the participant's answers.

5. RESULTS

The results of the experiment are shown in Figure 6[4]. For the analysis we ran comparative tests to measure the effects of the long-arm illusion induced with our vibrotactile condition in comparison with the traditional tapping condition. We ran a Wilcoxon Signed-Rank test at the 5% significance level for the *Ownership*, *Proprioception* and *Comfort* variables, and a paired t-test at the 5% significance level for the *Perceived Length* variable. Table 1 lists all the calculation details related to the following findings:

[4]RDI (raw data, description and inference) plot created with Yarr (github.com/ndphillips/yarrr)

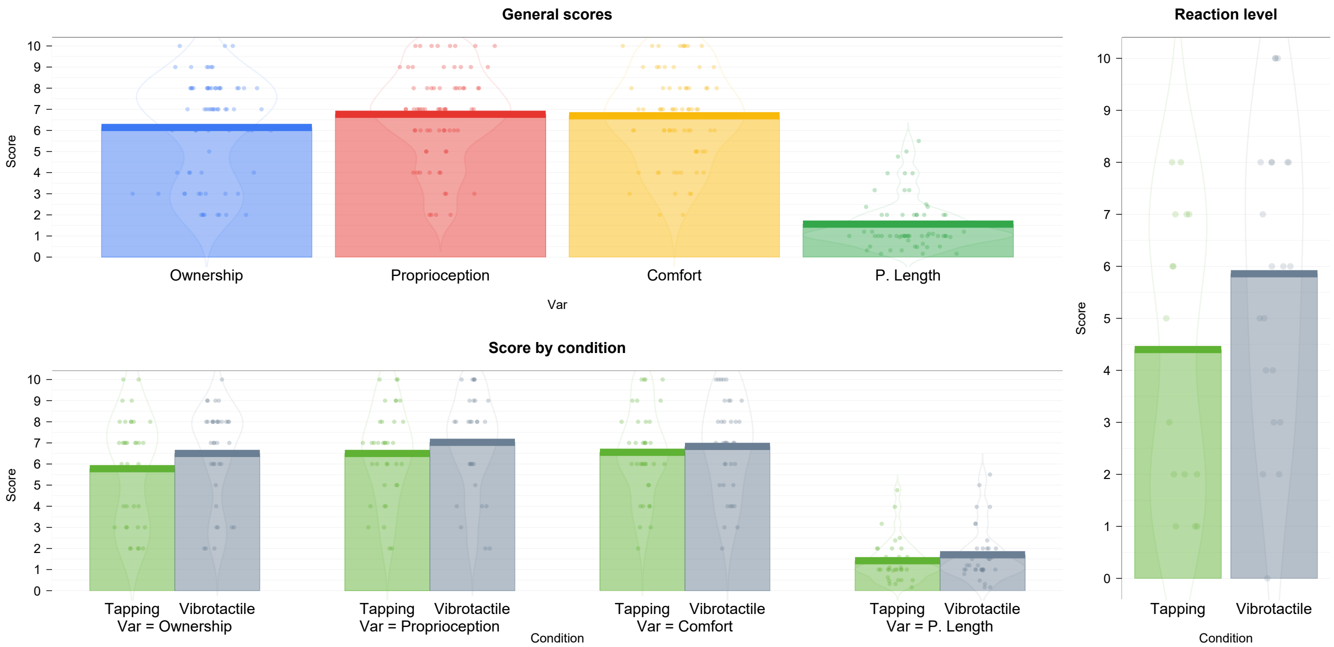


Figure 6: Plot corresponding to the dependent variables (ownership, proprioception, comfort and perceived length) showing (top) the general scores, (bottom) the scores ranked by experiment condition, and (right) the reaction levels.

- We found a significant influence of the elongated arm on **ownership** for the *Tapping Condition* (M=6.5, SD=2.171) and the *Vibrotactile Condition* (M=7.028, SD=2.210), reporting an effect of medium size (0.247).
- We found a significant influence of the elongated arm on **proprioception** for the *Tapping Condition* (M=5.778, SD=2.520) and the *Vibrotactile Condition* (M=6.50, SD=2.299), reporting an effect of medium size (0.348).
- We found no significant influence on the **comfort** variable for the *Tapping Condition* (M=6.555, SD=2.104) and the *Vibrotactile Condition* (M=6.833, SD=2.236).
- We found a significant effect of the elongated arm on the **perceived length** for the *Tapping Condition* (M=142%, SD=0.991) and the *Vibrotactile Condition* (M=170%, SD=1.267), the effect size is 0.350, with a standardized mean confidence interval of [-0.554; 0.010].

5.1 Subject Reaction

As described above, to draw further conclusions regarding the body ownership, a sudden event was presented to the participants at the end of the third phase. While doing the experiment, every participant (if previously agreed) was filmed to offer the possibility to recapture missed reactions during the study reviewing the video footage. The shown reactions were put into a scale from 0 to 10. If the participant did not show any signs of reaction, the value equals 0. If the participant showed a full reaction, like trying to protect his arm or showing full surprise reactions, like heavy breathing, then the value equals 10. The team did not only look at the twitching of the arm, but also included the surprise and fear reactions like laughing anxiously into the value. The presented reactions were noted as a comment to differentiate the values. The values of this subjective variable, indicate that almost 50% of the participants reacted noticeably to the sudden event (M=5.25, SD=2.872), while the *Tapping Condition* (M=4.4, SD=2.746) presented a lower reaction level than the *Vibrotactile Condition* (M=5.857, SD=2.869).

5.2 Simulator Sickness

Although the participants kept a seated position during the experiment and were instructed to look forward avoiding fast head movements to reduce nausea among other simulator effects, we asked the participants to answer the Simulator Sickness Questionnaire (SSQ) [23] before and after the experiment. We analyzed the data with a non-parametric Wilcoxon Signed-Rank test at the 5% significance level. There are no significant increases in the condition of the participants between before (M=0.187, SD=0.143) and after the experiment (M=0.131, SD=0.065).

5.3 Presence

The participants had to judge their level of presence on the basis of the Slater-Usoh-Steed presence questionnaire [32] after the experiment (M=4.828, SD=0.259) indicating a good sense of presence in addition to positive comments from some participants about the quality of the VR experience.

6. DISCUSSION

The results of the study indicate that the elongated-arm illusion was produced under both experimental conditions, which shows that the brief phases of matching visual-vibrotactile feedback could induce a compelling illusion. Moreover, the results show significant differences for the variables *ownership*, *proprioception* and *perceived length* between the conditions (see Figure 6), slightly benefiting the *Vibrotactile Condition*. This effect is most noticeable on the *perceived length*, showing a higher value by approximately 20% in this condition (although, as the virtual arm was elongated to double the starting size, most participants underestimated the length of the elongated arm in both conditions). The same trend is also present in the subject reaction measurements, where the *Vibrotactile Condition* resulted in behavior more closely matching natural threat responses with high body ownership.

We believe that an explanation of these differences is that our low-latency vibrotactile stimulus could be presented with less sensory discrepancy than the manually synchronized tapping. Although several efforts were made to provide high accuracy in the manual stimulation, the higher scores on the *Vibrotactile Condition* might be attributed to this discrepancy. In order to remove this confounding factor in our next iteration, we will track the position of the physical ball (i.e. IR-LED marker tracking) and transfer this onto the virtual ball in our 3D scene. Going further, other question could also be addressed regarding the vibrotactile device: ¿Could non-realistic (in terms of intensity) or non-synchronous feedback still be effective to support the body-transfer illusion in VR?

It is an interesting finding that the vibrotactile feedback was not just comparable to haptic feedback with a real ball in terms of the body-transfer illusion in this experiment, but even supported the illusion. Moreover, the automatic contact detection and feedback generation in the Unity3D implementation allows us to induce or reinforce such body-transfer illusions with brief phases of synchronized visual-tactile feedback at any time during a VR experience, without the need for a trained operator standing by to provide manual tapping feedback. We believe that this will allow us to reach similar effects in other illusions as well, such as the rubber-hand illusion [4]. Informal preliminary testing being conducted at our laboratory seems to support this impression.

Regarding our device, we are considering different technologies and techniques to improve the feedback, like haptic cues or dynamic vibration patterns [2]. Although we had a shape-recognition task to familiarize the participants with our device, it is still necessary to integrate more sensors and actuators to enable the feeling of textures, weight and detailed shapes. For example, recent studies focused on electro-tactile devices [13] and reported good results in terms of precision and performance for grasping tasks using tactors, which could offer a good alternative to address some issues related to location acuity and location sensitivity in order to implement effective shape-recognition techniques. In the same way, our experiment relied on the hand tracking provided by the Leap Motion sensor, but an approach in combination with optical LED marker tracking might further improve the device.

7. CONCLUSION AND FUTURE WORK

In this paper, we presented a technology framework featuring a device able to provide brief phases of vibrotactile feedback synchronized at low latency with visual feedback for the goal to enable and simplify the process to induce and reinforce body-transfer illusions in VR. We provided details on the implementation of the system including the concept of TCPs for accurate feedback generation, and we provided evidence from an experiment showing that the automatic visual-vibrotactile feedback can be used to induce a similar elongated-arm illusion as that which traditionally requires an operator to be present in order to stimulate the user with synchronized visual-haptic tapping feedback. Our results suggest that the approach may be transferred to other body illusions as well, thus providing the means to improve VR experiences of users in a variety of application fields.

In future work, we plan to extend the capabilities of the HapGlove with independent haptic drivers[5] for the actuators to offer improved reactive tactile feedback and richer vibration patterns, migrating from the current LRA technology to piezo-electric actuators, which, among other benefits, will provide wide-range and simultaneous variations in frequency and amplitude. For the glove itself, we plan to test other materials, to support the contact between the skin and the actuators. Also, in order to sense subtle user reactions, we plan to measure skin conductance as a stress response [3], with the integration of galvanic skin response (GSR) sensors [33] and include fingertip heart rate monitors. The haptic device will be made available as an open-source solution, allowing the interested audience to integrate it into their own projects.

Finally, further work will be mainly focused in the integration of other perceptual illusions with the purpose of use the gained experience in the creation of perceptually inspired user interfaces for VR.

[5] http://www.ti.com/product/DRV2667

8. ACKNOWLEDGMENTS

This work was partly supported by grants from the Deutsche Forschungsgemeinschaft.

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