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Designing visuo-haptic illusions for Virtual Reality applications using floor-based shape-changing displays

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Large-scale haptic displays offer the opportunity to create fully immersive experiences in Virtual Reality (VR). In particular, floor-based pin-array shape displays allow the creation of worlds with complex textures and walkable terrain patterns. However, the size and resolution of these terrains are typically limited by the physical constraints of the actuating hardware, negatively impacting the designing of VR experiences. To overcome these limitations, we propose the usage of visuo-haptic illusions for floor-based shape displays, effectively creating the illusion for terrains of a larger size and of a higher resolution. Following closely related prior work, we have conducted two user studies with 32 participants to determine the threshold of the visuo-haptic illusions and their impact on the perception of shape display resolution. Our findings offer potential solutions to the physical limitations of floor-based shape displays and provide insight into enhancing the overall VR experience to give more freedom to designers to create haptic feedback using pin-array shape displays.

Keywords: virtual reality; haptic experience design; visuo-haptic illusion

1 Introduction

Large-scale haptic interfaces offer the opportunity to design fully immersive virtual experiences by enhancing the digital content that is displayed through Virtual Reality (VR) headsets using haptic and proprioception cues. Using a combination of large-scale haptic interfaces such as walls (Joshi et al., 2022; Lopes et al., 2017; Suzuki et al., 2020a), stairs (Je et al., 2021), large objects (Suzuki et al., 2020b), and even terrains (Je et al., 2021), the designer of digital content can, in fact, recreate the immersive experience for cultural heritage sites (Christou et al., 2006) or for virtual tours in digital rooms that look realistic and that can change with the users' input (Suzuki et al., 2020a). This paper aims to shed some light on how large-scale haptic and proprioception cues are perceived on foot and how a designer could leverage these to recreate large-scale interactive and reconfigurable (shape-changing) terrains. Specifically, in this paper, we aim to characterize the role of the visuo-haptic illusion for large-scale shape-changing walkable pin-array displays - as seen in the work by Je et al. (2021).

Pin-array shape displays emerged as a popular type of large-scale haptic displays, using actuators to manipulate the pins' height and create various shapes and textures. They allowed designers to generate complex feedback previously unfeasible with small-scale haptic displays. Je et al. (2021) introduced a shape display that dynamically renders custom terrain patterns, such as dynamic terrains and staircases. However, despite the advantages of large-scale pin-array haptics, there are physical limitations that must be considered when designing the haptic feedback for the user's experience in VR.

First, floor-based shape displays require a large enough physical space for the user to freely explore the environment. Typically, these large shape-changing displays are expensive and demand intense labor and resources for fabrication, making it difficult to easily scale up their size. However, this is a problem because even the largest floor-based pin-array shape display with a surface of 180 cm x 60 cm was proven to not have a sufficient area for realistic VR experiences (Je et al., 2021). This brings us to the second limitation - the low resolution. While some shape-changing interfaces cover room-scale environments (Teng et al., 2019) and are designed with modular architecture (Suzuki et al., 2020b), the tiles have a surface of 30 cm x 30 cm. This resolution deprives the opportunity to render objects accurately and with high precision.

To overcome these physical limitations, we propose exploring the use of visuo-haptic illusions in VR, particularly angle redirection and scaling up. These illusions can be employed to render digital objects that are bigger or oriented differently from their physical counterparts or simply to increase the perceived resolution of the rendered objects. This illusion, in practice, makes it possible for users to experience more accurate and larger digital spaces, although their actual physical dimensions are smaller than the digital representations. While visuo-haptic illusions have been explored previously for hand interactions (Abtahi & Follmer, 2018), they have only been used in the tabletop realm.

In this paper, we aim to empower designers to create highly realistic physical proxies for foot interaction of virtual objects that go beyond the physical constraints of the physical hardware, thus creating immersive and engaging digital environments. To achieve this, our research aims to understand the perception of visuo-haptic illusions. We, therefore, present two separate user studies. The first user study will determine the detection threshold values for visuo-haptic illusion techniques (angle redirection and scaling up) on foot-based devices in VR. The second user study will examine the effectiveness of visuo-haptic illusions in enhancing the resolution of haptic feedback. By exploring the potential of visuo-haptic illusions, our research may help designers create limitless and highly immersive virtual experiences for users.

2 Related works

In this part of the paper, we will first discuss the ongoing research on haptic feedback on feet, particularly haptic shoes, haptic floors, and floor-based haptic shape displays. Then we will discuss visuo-haptic illusions.

2.1 Haptic feedback

Haptic feedback is a type of sensory information that is conveyed through the cutaneous senses (Nilsson et al., 2018). It is processed by somatosensory pressure receptors, which provide information about acceleration and physical contact with objects (Waller & Hodgson, 2013). Haptic feedback is created by controlling the tactile or kinesthetic properties of an object or interface (MacLean, 2000), which allows users to feel forces, movements, and other cutaneous sensations as if they are physically present in a virtual or remote environment (Marchal et al., 2013).

One way to enhance the user's ability to interact with and navigate through virtual or remote environments in real-time is to integrate haptic feedback in footwear, such as vibrotactile shoes or shoes with actuators. These wearable interfaces for the foot can be used for a variety of purposes, such as delivering dynamic information (Velázquez et al., 2012), generating virtual materials (Strohmeier et al., 2020), angular menu selections (Anlauff et al., 2018), performing pointing tasks (Horodniczy & Cooperstock, 2017), and language transmission (Hill et al., 2014).

Another approach to providing haptic feedback on the feet is using haptic floors. Haptic floors are surfaces designed to provide tactile feedback to the user's feet through actuators or other types of tactile transducers. While haptic floors can also be employed as a navigation tool (Hansen et al., 2022) or as means of communication (Visell et al., 2009), they also can be used to generate different ground materials like stones and gravels (Visell et al., 2009), to imitate the sound of crinkling or crunching of fragile structures (Okamoto et al., 2013), and to create a sensation of walking while the user is seated (Kato et al., 2017). While these studies focused mainly on the methods for generating the haptic feedback, our research focuses on expanding the design space using a method that overcomes the physical scale and resolution limitations of generating haptic feedback on the feet.

Haptic shape displays are devices that render the shape of virtual objects, allowing users to perceive and interact with them through touch and force feedback. The shape displays could be used to render virtual environments that enrich the experience of navigating through VR. In fact, there are ongoing research projects on this subject. TilePoP (Teng et al., 2019) is a pneumatically-actuated array of cube-shaped airbags attached to the floor that pop up to render virtual objects available for whole-body interactions. Similarly, LiftTiles (Suzuki et al., 2020b) is an array of modular inflatable actuators used for generating room-sized interfaces. However, both systems have load tolerances that are not sufficient to sustain a human walking on them. Moreover, they have a low resolution, as the tiles in these systems are 30 x 30 cm, making it impossible to render objects of smaller sizes or with small details. One of the projects that tackle these issues is Elevate, a walkable dynamic pin array that is used to render various shape-changing terrains by changing the height of individual pins (3x3 cm) in response to virtual events (Je et al., 2021). The authors, however, have acknowledged two issues with Elevate - limited terrain coverage and short vertical displacements of the pins. Although they also recommended using "space-folding" or redirected walking techniques, they mention that increasing the number of pin rows or the pin height will raise hardware costs or the time necessary to render the terrain. To tackle these limitations while also considering the problems of scalability and low resolution, we suggest utilizing visuo-haptic illusions.

2.2 Visuo-haptic illusion

In the case of sensory conflicts, vision takes precedence over touch, causing people to perceive the visual shape of the object over its tactual shape (Rock & Victor, 1964). This visual dominance effect is exploited by the technique of pseudo-haptic feedback that modifies the perceived material and geometric properties of the passive objects by manipulating the visual stimuli (Lécuyer et al., 2009; Ujitoko & Ban, 2021). One of the techniques that are built upon the visual dominance effect is haptic retargeting which is used to create a haptic sensation of multiple virtual objects by repurposing a single haptic proxy object (Azmandian et al., 2016). Ban et al. (2012a; 2012b) used redirection to adjust the position of the user's hand when changing the shape of virtual objects. Another commonly utilized illusion is the manipulation of the control-display (CD) ratio - the ratio between the physical displacement of the input device and virtual output displacement. The CD ratio can be used to non-linearly increase the user's hand reach in VR (Poupyrev et al., 1996) and simulate the linear translation and stretching of objects using physical proxies (Feick et al., 2021).

Abtahi & Follmer (2018) applied three visuo-haptic illusions (retargeting, redirection, and scaling) to improve the perceived resolution and smoothness of tabletop-like displays in VR. While this paper is based on the methodology introduced by Abtahi & Follmer, in this paper, we are instead exploring the visuo-haptic illusions specifically on foot-based shape displays, such as Elevate (Je et al., 2021).

Abtahi & Follmer (2018) utilized retargeting to shape displays, expanding the perceived interaction area. Through redirection, they manipulated linear paths and virtual finger placement to induce the illusion of navigating sloped edges (angle redirection). They upscaled virtual objects and mapped onto larger physical counterparts via increased C/D ratios (scaling up). They addressed pin speed limitations in rendering the virtual movement with retargeting and vertical redirection. Due to hardware differences, we will focus solely on angle redirection and scaling up (Figure 1).

The rest of this paper aims to estimate the boundaries of visuo-haptic illusions for the foot and to discover any differences in the perceived performance of foot-based shape displays when the visuo-haptic illusions are applied.

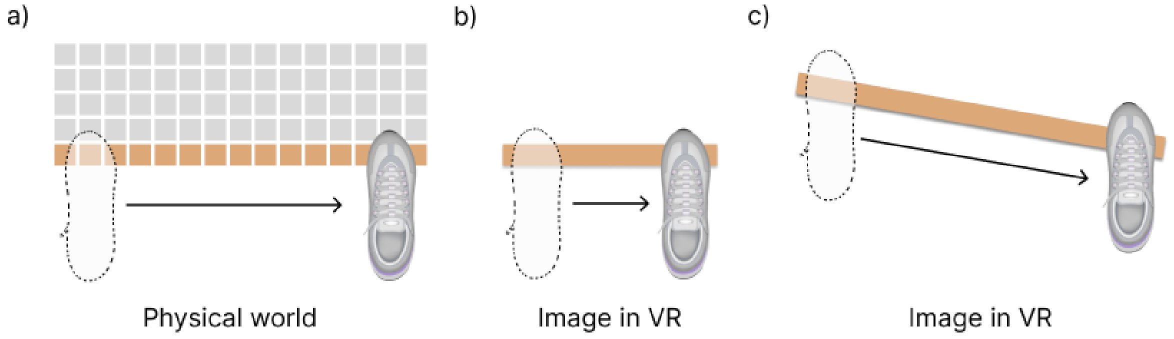

Figure 1. (a) The user moves their foot from left to right along the shape display. (b) When the scaling-up technique is applied, the virtual foot's displacement is scaled down. (c) When the angle redirection technique is applied, the virtual foot is redirected.

3 Methodology

This research aims to provide designers with advanced insights inyo the impact of visuo-haptic illusions on the perception of floor-based shape displays in VR. We focus on two specific illusion techniques: angle redirection and scaling up, as defined by Abtahi & Follmer (2018).

In the first user study, we aim to estimate the detection thresholds for visuo-haptic illusions techniques. The detection threshold refers to the minimum level of stimulus intensity required for an individual to detect the presence of an illusion. If the stimulus intensity falls below this threshold, there is no semantic violation caused by discrepancies between visual and tactile sensory input (Padrao et al., 2016).

In the second user study, we build upon the results obtained from the first user study and apply visuo-haptic illusions on pin-array shape display below the thresholds of cognitive incongruity. We investigate whether the visuo-haptic illusions enhance people's perception of the resolution of the pin-array shape display while rendering virtual objects.

4 User study 1: Determining the thresholds for visuo-haptic illusions

4.1 Study design

This study was designed to closely mirror the work of Abtahi & Follmer (2018). We used a within-subject design in which two conditions (barefoot and shoes) and two types of stimuli (angle and scale) were tested on 16 participants. The participants were asked to experience the wooden bar while being presented with the bar’s virtual image in VR (Figure 2). While the physical bar remains unscaled at 0 degrees throughout the study, the virtual image of the wooden bar was altered according to the stimulus that is being evaluated in each trial. For angle redirection, the virtual bar was rotated at one of 13 different angles (from 0° to 65° with 5° intervals). For scaling up, the virtual bar was scaled down to one of the five scale factors: 1x, 1.14x, 1.33x, 1.6x, and 2x. After the trial, we asked participants to rate their confidence in whether they perceived an illusion. The order of samples was randomized. Each condition and stimulus have been balanced.

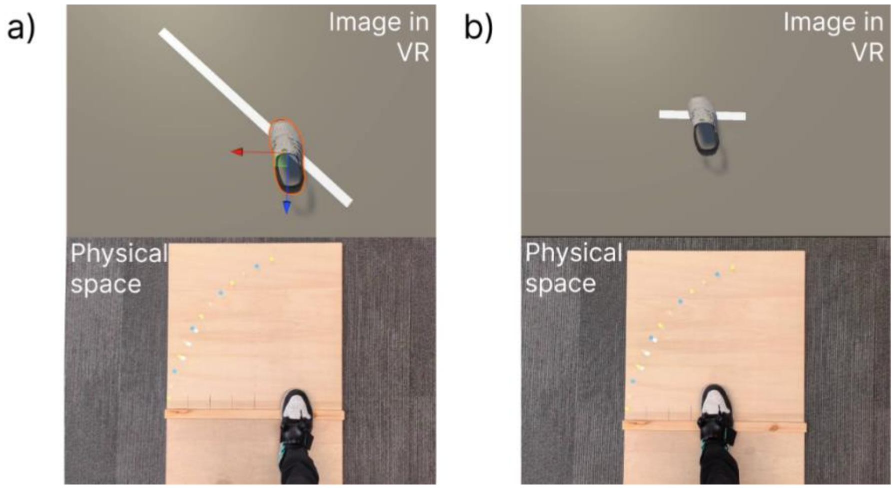

Figure 2. a) Mapping a horizontal line onto a slanted line using angle redirection. b) Mapping a longer line onto a shorter line using scaling-up.

4.2 Materials

To determine the boundaries of visuo-haptic illusions independently from the shape display, we designed and constructed a passive haptic device: a wooden rod placed on a wooden plate. The size of the rod was chosen by referring to the shape display presented in the previous research (Je et al., 2021). The width of the rod is 30 mm, the height is 30 mm, and the length between the two endpoints is 600 mm. The rod can be rotated and fixed at angles from 0° to 90°, with 5° intervals. Moreover, the length of the rod can be modified by sliding the endpoint. We placed two trackers at two of the corners of the wooden board, next to the wooden rod, to determine the placement of the virtual rod. In addition, we prepared shoes of different sizes for the participants to wear to compare the effect of barefoot vs. shoes.

4.3 Participants

We recruited 16 participants from our institution - 5 females, and 11 males aged 19-30 years old (M=23.8, SD=3.83). Participants were provided with shoes of five different sizes: 240mm, 250mm, 260mm, 270mm, and 280mm. Their barefoot sole length was measured, and they were instructed to put on the shoe that fits them the best. The average foot size of the participants is 249.9 mm (SD = 16.54), and the average shoe size is 260.6 mm (SD = 15.26). 12 participants reported being familiar with VR, 10 participants reported being familiar with haptic interfaces, and all participants reported not being familiar with visuo-haptic illusions. Participants were compensated with 20 USD in local currency for their time.

4.4 Procedure

We attached a Vive tracker to the instep of the participant's right foot and calibrated the shoe's virtual image to fit the foot. This tracker allows us to compute the foot location in the virtual world. The participants were provided with the HTC Vive headset and headphones playing white noise to avoid distractions and any audio cues that may help them.

We started the study by informing the participants of the goal of the study and its structure. The study procedure and concept of visuo-haptic illusion were introduced to the participants through a short training session, where two trials were presented, one with the obvious application of the illusion and one without the illusion.

The study consisted of two main parts exploring angle redirection and scaling-up techniques, respectively. As we wanted to investigate if the presence of the shoe influences the perception of the illusion, we repeated each part twice, one with the participants wearing a shoe and the other barefoot. The order of the four parts was balanced following a Latin square design. Each of the parts consisted of a different number of trials. During each trial, one of the stimuli interventions was evaluated. Each trial was repeated four times. So, each participant experienced a total of 144 trials (52 for angle redirection, 20 for scaling-up; each repeated twice). For a trial, the minimum exploration time given to the participants was 12 seconds. After each trial, the participants were asked these two questions:

1. Did you perceive an illusion?
2. How confident do you feel about your answer from 1 to 5? Choose 1 for not confident at all and 5 for very confident.

Along with the answers to the given questions, we collected a NASA Task Load Index (TLX) (Hart & Staveland, 1988) and the simulator sickness (SSQ) (Kennedy et al., 1993) questionnaires and collected the raw data on how each region of the sole interacted with the passive haptic device.

4.5 Results

Our analysis of results closely follows, again, the work of Abtahi & Follmer (2018). The detection ratio of the illusion in the sample is the number of times the illusion in the sample was detected with the confidence level of a minimum of 3 by the participant divided by the total number of times that particular sample was presented to the participant. To compute the detection threshold for each type of visuo-haptic illusion technique, we determined the detection ratio for each participant at each sample point, averaged the detection ratios across all participants, and fit the resulting data points into a psychometric function with real a and b (Steinicke et al., 2009) with 95% confidence bounds:

$$f(x) = \frac{1}{1 + e^{ax+b}}$$

The point of subjective equality, or the Conservative Detection Threshold (CDT), is established as the value where the average detection ratio reaches 0.5. Suppose the detection ratio falls below the CDT. In that case, the participants were probably unable to detect the stimulus, as their detection performance would have been equivalent to a random guess, resulting in a 0.5 average detection ratio. We referred to prior research to determine the Detection Threshold (DT) (Abtahi & Follmer, 2018; Matsuoka et al., 2002; Steinicke et al., 2009) and selected the value that corresponds to an average detection ratio of 0.75.

We then analyzed the results for the angle redirection and the scaling up. Each of these parts was repeated for two different foot conditions: barefoot and with shoes on. For the angle redirection analysis, we applied the redirection to create the illusion of a horizontal line being slanted. For the barefoot condition, the DT of redirection techniques is 43.28° with a = -0.08978 and b = 2.787. For the condition of having shoes on, the DT of redirection techniques is 46.44° with a = -0.0851 and b = 2.8533. For the analysis of scaling up, we applied the scaling up to map a shorter horizontal line to a longer one. For the barefoot condition, the DT of scaling-up techniques is 1.48x with a = -6.995 and b = 9.318. For the condition of having shoes on, the DT of redirection techniques is 1.54x with a = -5.758 and b = 7.807.

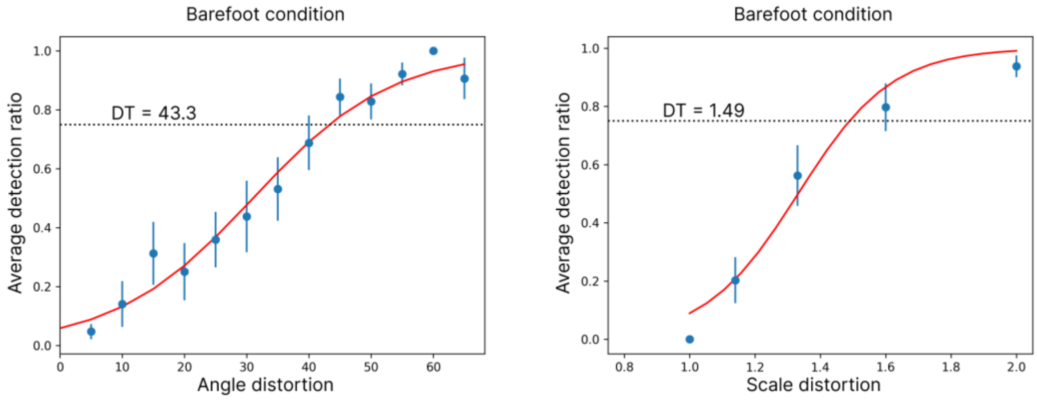

Figure 3. Average detection ratio against Angle distortion graphs. The detection threshold on the left (barefoot) is at 43.3°. The detection threshold on the right (with shoes) is 46.4°.

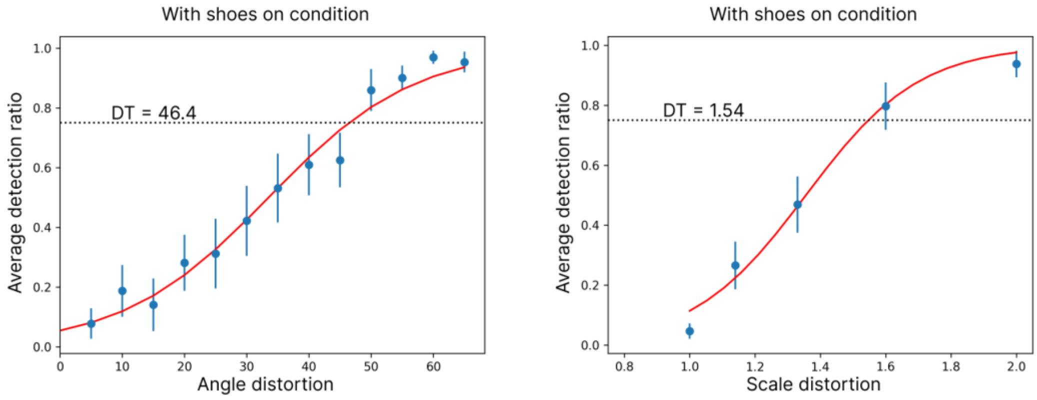

Figure 4. Average detection ratio against Scale distortion graphs. The detection threshold on the left (barefoot) is at x1.49. The detection threshold on the right (with shoes) is at x1.54.

A Wilcoxon signed-rank test showed that for the angle redirection, there is no statistically significant difference between wearing shoes and the barefoot case (Z = -1.664, p = 0.100). Similarly, a Wilcoxon signed-rank test did not show a statistically significant difference (Z = -0.149, p = 0.881) for scaling up in the barefoot and shoe-wearing conditions.

We then looked for patterns in how the users used their feet to explore the passive prop. As illustrated in Figure 5, in the barefoot condition, the participants mainly used their toes and metatarsals when exploring the passive haptic device with their feet. However, when the participants wore a shoe, their explorations involved the middle part of the sole. We counted how many times the participants touched the bar with a particular part of the foot and divided the result by the total number of times a participant touched the bar with the foot.

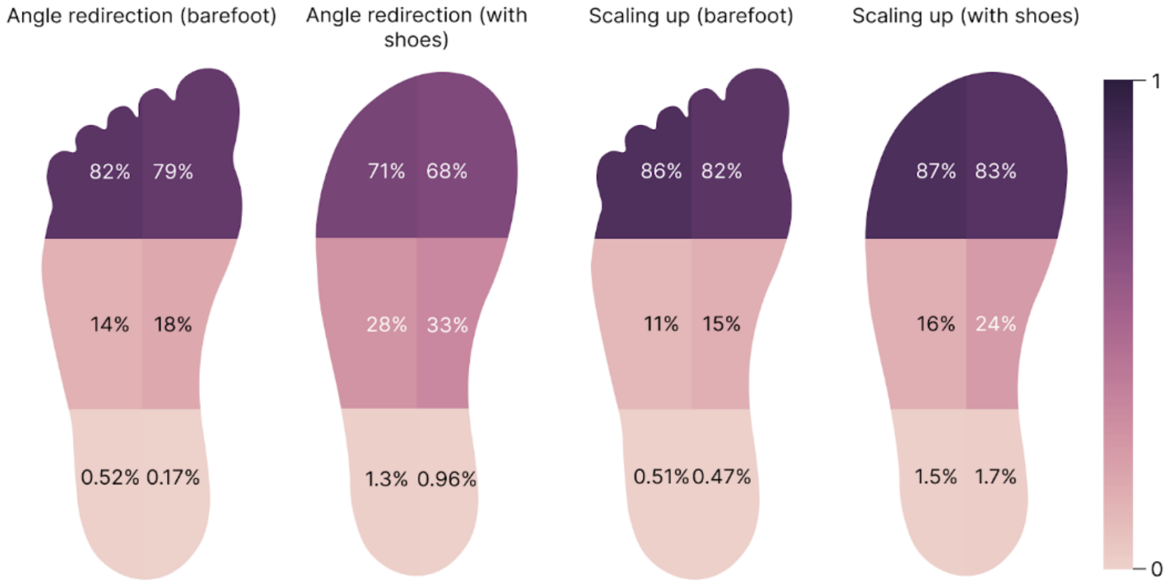

Figure 5. Heatmaps of the distribution of haptic device interactions across the sole's different parts throughout the study, presented as a percentage.

The results of TLX are shown in Figure 6. We performed a two-way ANOVA test on the workload scores. We found no statistically significant difference in mean interest in workload between footwear conditions (p = 0.639), but there was a statistically significant difference between types of illusion (p = 0.003). Moreover, there was no statistically significant interaction between footwear conditions and the types of illusion (p = 0.902).

The SSQ scores for angle redirection are 41.14 and 45.11 for “barefoot” and “shoes on” conditions, respectively. The SSQ scores for scaling up are 25.25 and 30.15 for “barefoot” and “shoes on” conditions, respectively. Overall, the “angle redirection” part was more demanding than the “scaling-up” condition.

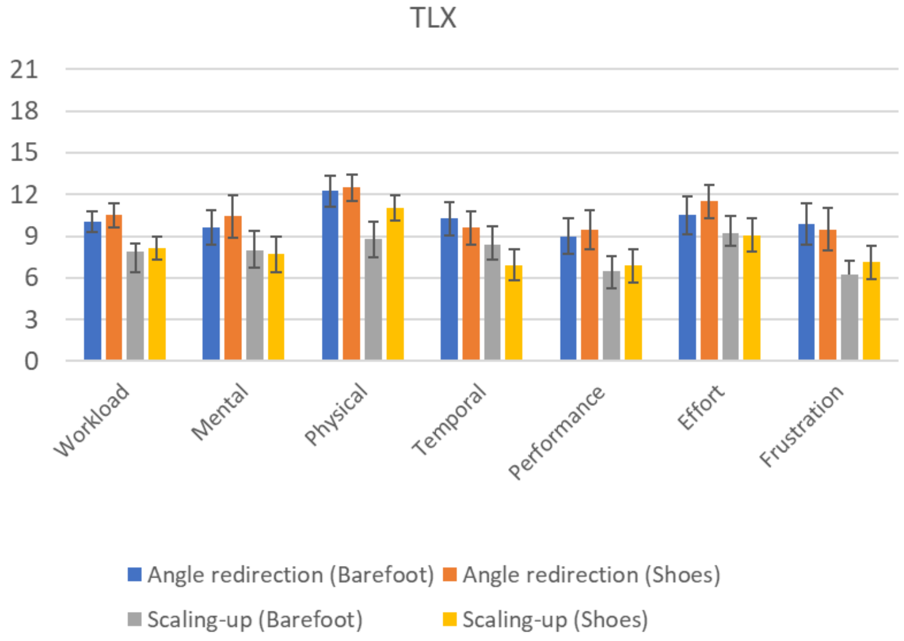

Figure 6. Raw TLX score for the cognitive load in study 1. The vertical axis indicates the TLX score.

5 User study 2: Improving the perceived resolution of shape displays

5.1 Study design

Similar to the first study, the second study closely follows the work of Abtahi & Follmer (2018). In this study, we proceed with only the "shoes on" condition, as there was no statistically significant difference between barefoot and with shoes on (Section 4). We employed a within-subject design with two types of stimuli (angle and scale), and the study was tested on 16 participants. The participants were asked to experience two types of passive wooden props in VR: 1) a linear line for angle redirection (Figure 7) and 2) a 3-dimensional hemisphere for scaling up (Figure 8). During each trial, two wooden props were presented, one matching the dimensions of virtual objects (no illusion) and the other with a different geometric arrangement than the virtual object (with illusion). There were four uniformly distributed distortion levels examined for each type of stimulus. The range was selected based on the results of the first study. The upper bound for angle redirection is set to 40° by rounding down the DT (46.44°) from the first study, and we tested four different angles 10°, 20°, 30° and 40°. For scaling up, we set the upper bound to 1.54x, which is the DT found in the first study. The four tested scale factors are 1.08x, 1.23x, 1.38x, and 1.54x, having common difference factors between the scales.

Figure 7. The horizontal line used for angle redirection and all angles that are evaluated (10˚, 20˚, 30˚, 40˚)

Figure 8. The unscaled hemisphere and hemispheres are scaled by 1.08x, 1.23x, 1.38x, and 1.54x.

5.2 Materials

In this study, we utilize ten passive devices, five for angle redirection and five for scaling up. Each device included a 600x600mm wooden board and 400 wooden pins (30x30 mm). The wooden boards were divided into 20x20 grids, and each pin was positioned on the grid to "render" different objects, providing a resolution similar to that of a shape display. We switched between different passive devices when switching displays. During the experiment, participants stood on a 600x600mm board firmly placed against one side of the passive device, with the board height matching the platform height of the passive device. Before starting the experiment, we positioned two trackers at the board's corners to align the display object. The remaining apparatus, including the HMD, noise-canceling headphones, and trackers, is the same used in the first study.

5.3 Participants

We recruited 16 participants from our institution: 3 females and 13 males aged 20 to 30 (M = 24.25, SD = 2.73). The average shoe size was 282.19 mm (SD = 13.11). 11 participants reported being familiar with VR, 3 participants reported being familiar with haptic interfaces, and all participants reported not being familiar with visuo-haptic illusions. Participants were compensated with 15 USD in local currency for their time.

5.4 Procedure

We attached the VIVE tracker to the instep of their right foot to prepare the participants for the study. Then, we carefully calibrated the virtual image of the shoe by adjusting its dimensions. Next, we provided participants with the HTC Vive headset and headphones with white noise to minimize distractions and prevent any audio cues.

We did not inform participants of the actual goal of the study. Instead, they were asked to compare the performance/resolution of different shape displays. The hardware was hidden from the participants. We only demonstrated a video of shape displays and introduced the concept of resolution. To familiarise participants with the study process, one sample was presented to them during the training session. There was no time limit, so they could freely explore the surface of the shape display.

Our study consists of two parts, one exploring the angle redirection (Figure 9) and one exploring the scaling up (Figure 10). The order between them was selected randomly. In each part, 4 different stimulus interventions were evaluated. Each was tested twice. Therefore, 8 trials were conducted, and they were arranged randomly.

Each trial includes two samples. As a first sample, we examine haptic rendering without illusion, i.e., the render corresponds exactly to the virtual object. The second sample uses the visuo-haptic illusion to render the virtual object, so the resolution enhancement technique was applied. In each trial, samples are also ordered randomly. In total, there were 16 trials that consisted of 32 samples. For each trial, the minimum exploration time given to the participants was 12 seconds.

Image in VR

Physical space
(Redirection is applied)

Physical space
(Redirection is not applied)

Figure 9. (Left) The visual image in VR in both with and without angle redirection cases. (Middle) Mapping a horizontal line onto a virtual slanted line using angle redirection. (Right) 1-to-1 mapping of a slanted line onto a virtual slanted line with no illusion.

Image in VR

Physical space
(Scaling-up is applied)

Physical space
(Scaling-up is not applied)

Figure 10. (Left) The visual image in VR in both with and without scaling-up cases. (Middle) Mapping a smaller virtual hemisphere to a larger hemisphere that has a higher resolution. (Right) 1-to-1 mapping of a smaller virtual hemisphere to a physical hemisphere with no illusion.

After each trial, we asked participants the following three questions:

1. Which display did you think was the higher resolution? 1 or 2?
2. Which display did you think was smoother? 1 or 2?
3. Which one did you prefer? 1 or 2?

Along with the answers, we collected data on which region of the sole interacted with the passive haptic device, and which pins were interacted with the most. We conducted a NASA TLX and a SSQ surveys.

Results

Similarly to the reference paper (Abtahi & Follmer, 2018), we determined the proportion of responses where the sample containing the illusion was identified as possessing higher resolution, smoothness, and preference by the participants. Based on the percentages calculated from the responses, we can analyze the preference of participants between two images - one with an illusion and one without.

In the first part of the study, the percentages of responses stating that the sample with angle redirection applied was higher resolution, smoother, or more preferable decreased as the angle of rotation for redirection increased, with 40° being an outlier (Figure 11). Specifically, for the 10° trial point, 62.5% of responses indicated that the illusion produced higher resolution, 81% indicated that it was smoother, and 72% indicated that it was preferable. However, the percentages then decreased for the 20° and 30° trial points, ranging between 53% and 62.5% for "higher resolution" and "smoother", with a slight majority of all responses still favoring the illusion. However, the portion of responses selecting 20° and 30° as preferred render are 53% and 50%, respectively, which is close to a random guess. For the 40° trial point, the percentages increased again, with 72% indicating that the illusion produced higher resolution, 78% indicating that it was smoother, and 62.5% indicating that it was preferable.

Overall, for the angle redirection, the percentages suggest that below the semantic violation, participants generally thought of the renderings with the illusion as smoother and having higher resolution. Although the pixel displays have a fixed resolution of 30x30 mm, users can have a smoother feeling up to 40 degrees by applying angle redirection to map the horizontal line to a slanted line.

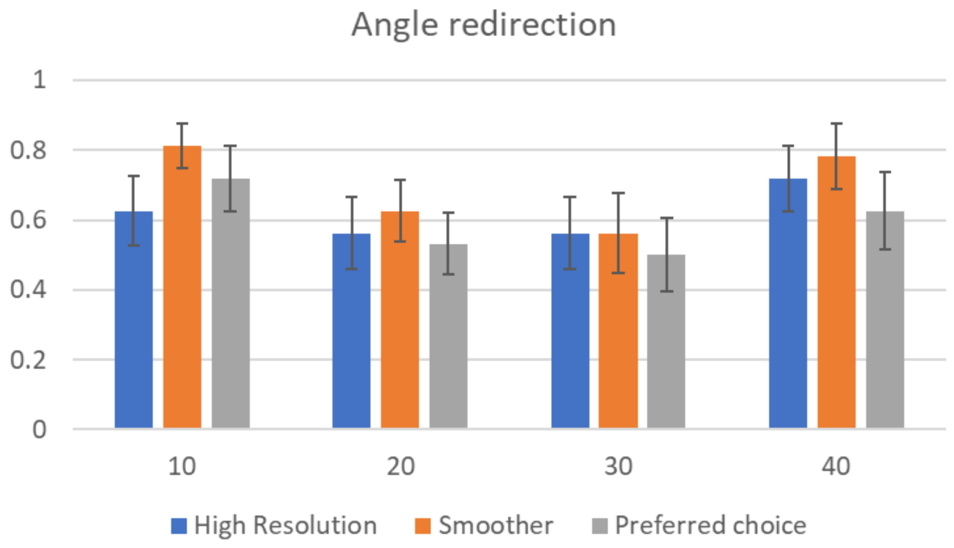

Figure 11. The proportion of respondents perceiving the sample with illusion as having higher resolution, smoother texture, and preferred choice.

In the second part of the study, we attempt to increase the perceived resolution of the hemisphere. To do this, we mapped it to a larger hemisphere with a more detailed rendering. The results showed that the majority of the time the usage of visuo-haptic illusions increased the resolution of shape display. In Figure 12, it can be seen that for all distortion levels, more than 67% of responses indicated the sample with illusion as "higher resolution." However, as the scale factor increased, the smoothness of the display generally decreased. At the scale factor of 1.08x, the percentage was 66%, while at the largest scale factor of 1.54x, the percentage was 56%.

Nevertheless, all percentages were higher than 50%. It means that the scaling-up technique enhances the smoothness of the shape display. Lastly, up until the 1.38x scale factor, participants preferred the sample with the illusion to the sample without the illusion. The percentage at the 1.54x scale factor is 47%, which is lower than 50%. It suggests that people did not prefer the hemispheres scaled by 1.54 times, though it was generally higher resolution and smoother.

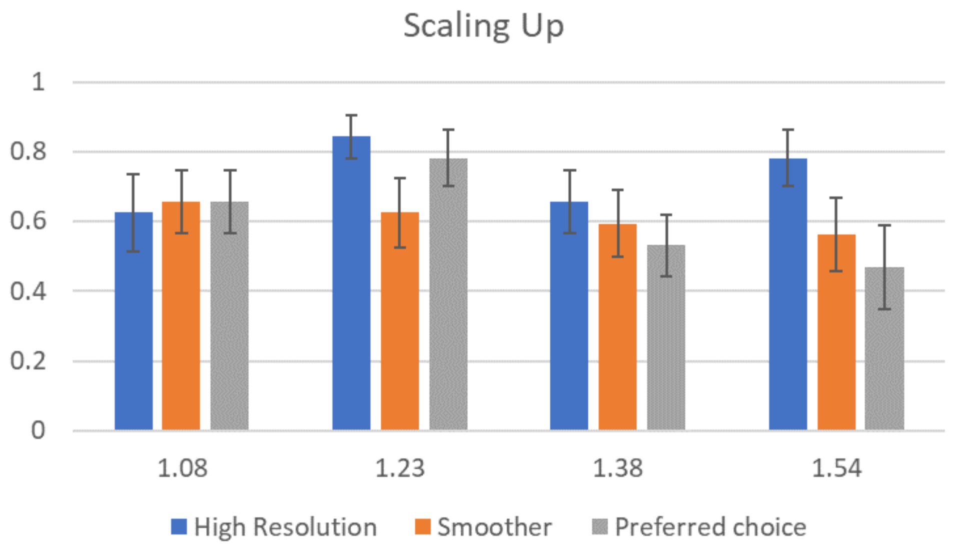

Figure 12. The proportion of respondents perceiving the sample with illusion as having higher resolution, smoother texture, and preferred choice.

Interestingly, Figure 13 shows that in the second study, people used the upper and middle part of the sole quite similarly to explore the horizontal line geometry. In contrast, they used their whole foot to interact with the render of the hemisphere. The heatmaps in Figure 14 illustrate the distribution of interactions across the pins of the shape displays throughout the study. It can be seen that users explored all lengths/shapes for both types of geometry.

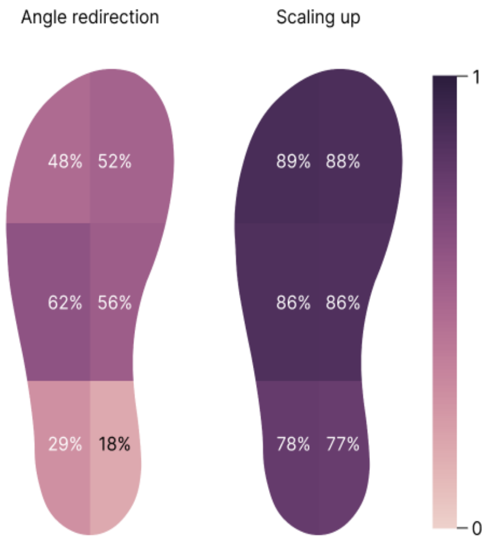

Figure 13. Heatmaps of the distribution of haptic device interactions across the sole's different parts throughout the study, presented as a percentage.

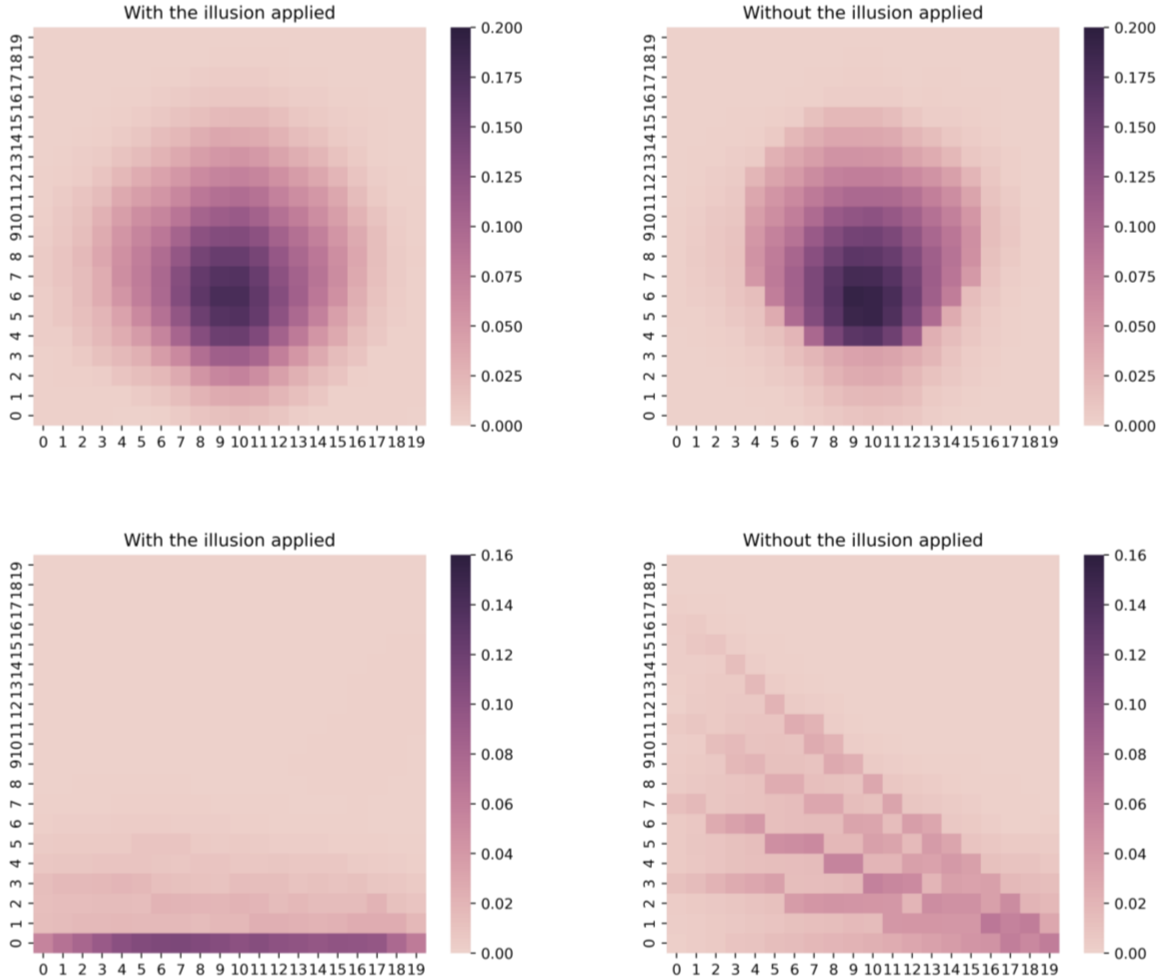

Figure 14. Heatmaps of the distribution of interactions across the pins of shape display throughout the study 2.

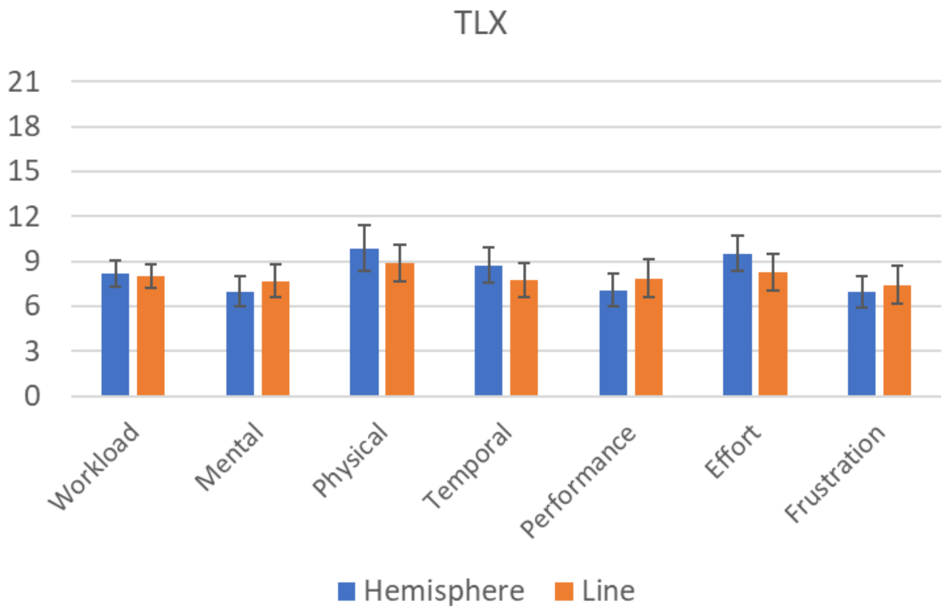

Figure 15. Raw TLX score for the cognitive load in study 2. The vertical axis indicates the TLX score.

The comparison between TLX scores for two parts of the second user study is shown in Figure 15. No statistically significant difference was found for all categories, according to the t-test. The average total severity score for the scaling up is 32.7, while for the angle redirection, it is 32.3. A t-test reveals no statistically significant differences between the two geometries.

6 Discussion

The combined results of our studies shed light on the detection thresholds for two types of visuo-haptic illusion techniques: angle redirection and scaling up. We found that it is possible to map a horizontal line to a line that is slanted up to 46.44° without a discrepancy between delivered visual information and tactual sensation. Also, it is possible to map a bar to a render that has been scaled up to a maximum scale factor of 1.54x without resulting in a sensory conflict. These results align well with the outcomes reported by Abtahi & Follmer (2018), wherein angle redirection and scaling-up thresholds exhibited values of 49.5° and 1.90x, respectively. Although the angle redirection displays similar boundaries for the finger and foot, there is a minor difference in the scaling-up factor. We hypothesize that the perception of angle is independent of the displacement magnitude of the moving body part. As a result, the angle redirection DT we obtained was similar. Alternatively, we hypothesize that the perception of the scale factor is different from the tabletop and floor-based display because there may be an absolute threshold in the distance beyond which sensory conflict cannot be prevented.

Through the second study, we confirm that we can simulate virtual objects by making smoother and higher-resolution renderings of surfaces that are, in fact, not smooth using visuo-haptic illusions. However, compared to the findings of Abtahi & Follmer (2018), which had 92% of participants pick the hemisphere with illusion as their preferred choice, our outcomes demonstrate that the samples with illusion were not preferred at greater scale factors (47% at 1.54x scale factor). The participants are more sensitive to the size of the hemispheres when touching with their feet than when touching with their fingers. We postulate that the center of gravity of the participant's body changes constantly when touching the hemisphere with their foot, whereas, in the case of a finger, the body remains unmoved. Therefore, the scaled-up (1.54x) hemisphere for the illusion might have caused the discrepancy between the senses.

As a result, our findings from the two studies carry meaningful implications. Firstly, unlike previous work (Abtahi & Follmer, 2018) that primarily focused on the application of visuo-haptic illusion in the tabletop realm, in our study, we extended the scope to investigate the effectiveness of the visuo-haptic illusions on the floor-based pin-array shape displays. It is particularly crucial for VR experiences that require full-body interaction within larger virtual space, such as redirected walking (Razzaque, 2005), where other locomotion techniques disrupt the immersion and user experience. In our research, we established an effective range of visuo-haptic illusions applicable to floor-based pin-array shape displays, thereby offering valuable insights for designers to leverage these techniques. By understanding terrains and how they can be modified, as well as carefully manipulating the visual cues, designers can facilitate different illusions on foot-based VR interaction. For example, designers can devise terrains that dynamically shape-shift depending on the user's virtual reality perception. Furthermore, we have found that the type of shoes of participants or how they interact with the haptic interface has no discernible effect on visuo-haptic illusion, as described in the first study (Section 4).

This enables designers to apply illusions on various virtual setups, from outdoor terrain to indoor furniture, without being constrained by footwear.

Our work's outcome also confirms the possibility of overcoming the physical limitations of existing floor-based pin array shape displays (Je et al., 2021; Suzuki et al., 2020b; Teng et al., 2019), which are facing common constraints of limited size and inadequate resolution. It confirms the potential of the visuo-haptic illusions technique to expand the design space of floor-based pin-array shape displays. For example, one of the suggested applications of LiftTiles (Suzuki et al., 2020b) is rendering full-scale object mock-ups of large objects such as cars to assist with the design process. However, the size of one tile is 30 cm x 30 cm, which does not allow for accurate rendering of the smaller details. By applying the visuo-haptic illusions to these tiles, we can map smaller virtual objects to higher resolution larger render without changing any of the dimensions of the shape-changing interface. This approach holds significant potential in expanding the application of visuo-haptic illusions beyond the floor realm to diverse large haptic interfaces, such as haptic walls (Bouzbib et al., 2020), haptic doors (Hoshikawa et al., 2022) or stiff terrains (Chang et al., 2023).

7 Conclusion

In this paper, we applied visuo-haptic illusion to provide solutions to the physical limitations of previous floor-type display research. Our two user studies confirm that we can create an illusion to increase the virtual object's size (max 1.54x) and rotation (max 46.44°) without any discrepancy between virtual and physical objects. Also, we found that applying visuo-haptic illusion on floor-based pin array devices can increase the perceived smoothness and resolution of virtual objects. In conclusion, the two user studies with 32 participants corroborate that it is possible to create an illusion for floor-based shape-changing displays 1) to increase the size, 2) to rotate, 3) to smooth, and 4) to enhance the resolution of the perceived virtual object. These findings provide important guidelines that enable designers to enhance the immersive experience of VR applications through the use of visuo-haptic illusions.

While our approaches are effective, it is not without their limitations and areas where further improvement could be made. We have not explored the influence of different types of shoes on perception, as we provided the same type of shoes (with different sizes) for all participants in the study. Another limitation of our study is the absence of an exploration of various pin shapes, such as circular or hexagonal, which could potentially impact the perceived resolution and smoothness of virtual objects. Also, we did not investigate how the visuo-haptic illusion might be applied to materials with different levels of softness. These limitations suggest that further research is needed to better understand the impact of various types of shoes, pin shapes, and device materials along with levels of softness on the visuo-haptic experience. To further advance this research, potential future directions could involve exploring the feasibility of applying dynamic illusions to objects that are moving and shape-changing. Additionally, there is an interest in organizing design workshops with interaction designers to develop potential virtual reality applications that utilize the visuo-haptic illusion techniques for haptic user experiences (Schneider et al., 2021).

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