Visuo-Haptic Illusions for Improving the Perceived Performance of Shape Displays

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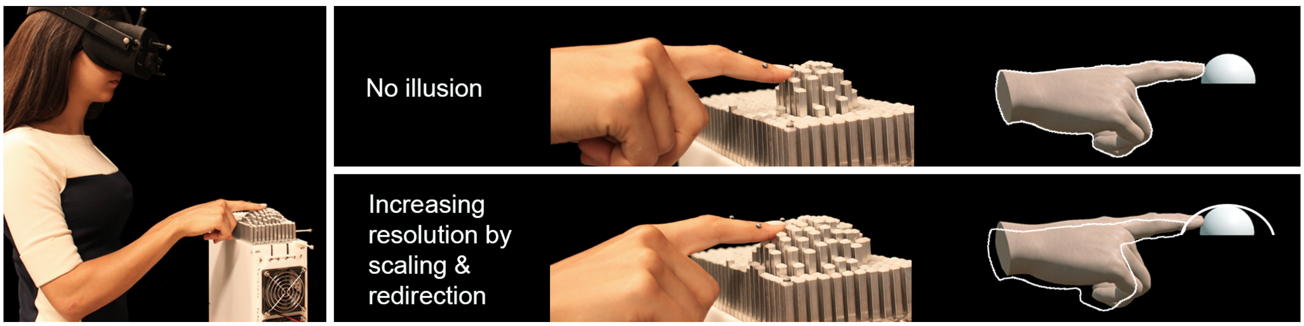

Figure 1. The user wearing a head-mounted display sees a small hemisphere. The tactile feedback is provided with a shape display. Instead of rendering the small hemisphere (top), the shape display renders a larger hemisphere with higher resolution (bottom) that is mapped to the virtual shape by altering the user's perception of scale and redirecting the finger.

ABSTRACT
In this work, we utilize visuo-haptic illusions to improve the perceived performance of encountered-type haptic devices, specifically shape displays, in virtual reality. Shape displays are matrices of actuated pins that travel vertically to render physical shapes; however, they have limitations such as low resolution, small display size, and low pin speed. To address these limitations, we employ illusions such as redirection, scaling, and retargeting that take advantage of the visual dominance effect, the idea that vision often dominates when senses conflict. Our evaluation of these techniques suggests that redirecting sloped lines with angles less than 40° onto a horizontal line is an effective technique for increasing the perceived resolution of the display. Scaling up the virtual object onto the shape display by a factor less than $1.8x$ can also increase the perceived resolution. Finally, using vertical redirection a perceived $3x$ speed increase can be achieved.

Author Keywords
Virtual Reality; Haptics; Illusion; Perception; Shape Displays.

ACM Classification Keywords
H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems-Artificial, Augmented, and Virtual Realities; H.5.2 [User Interfaces]: Haptic I/O

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INTRODUCTION
Recent advances in technology have brought Virtual Reality (VR) closer to a visually immersive experience. Haptic feedback technology, however, has not yet reached this level of realism, as users are unable to touch and manipulate virtual objects the same way they interact with real ones. Encountered-type haptic devices, such as shape displays, aim towards bridging this gap by providing a physical object to the user, as opposed to creating the sensation of force or tactile feedback. The advantage of encountered-type haptics over other solutions (externally grounded [34], wearable [9, 40], handheld [7], and mid-air [44, 37]) is that they do not require the user to wear a device or hold a controller. Moreover, they allow haptic exploration of virtual objects not only through a single point or finger tip, but with the entire hand.

Shape displays are matrices of actuated pins that travel vertically and can be used as an encountered-type haptic solution in VR, by rendering various 2.5D geometries [31]. However, the current size and cost of linear actuators and shape display hardware poses some limitations on their use as a haptic device [12]. These limitations include:

1. *Spatial resolution:* most shape displays use one actuator per pin, and the relatively large size of these actuators limits the resolution of the display. The low resolution affects the smoothness of the surface [19] and constrains the complexity of the content that can be represented in VR [30].

2. *Display size:* the cost and complexity associated with adding more actuated pins limits the size of the interaction area, the virtual space for which haptic feedback can be provided.

3. *Pin Speed:* in order to render various virtual elements, the shape display has to morph into different objects and surfaces. The speed of this deformation and the refresh rate of the display, however, is limited by the maximum speed of the actuated pins.

In this work, we propose techniques that use visuo-haptic illusions to address these limitations and improve the perceived performance of shape displays when used as an active haptic feedback device in virtual reality. Visuo-haptic illusions are perceptual illusions that take advantage of the visual dominance effect, the concept that when senses conflict often vision dominates [13, 17, 41]. These illusions include retargeting, used to map a single physical object to multiple virtual objects [3, 8], or redirection to modify the perceived properties of the physical object such as shape [4, 6, 5], size, texture, and stiffness [23, 24, 27]. These techniques, however, have not been applied as extensively to active haptic devices, such as shape displays. A better understanding of perceptual illusions and their application to shape displays enables rendering of complex physical shapes and improves how closely the perceived haptic feedback aligns with the virtual content.

We suggest two methods for improving the perceived resolution of shape displays. The first method uses linear redirection to map slanted edges of virtual objects to horizontal or vertical paths on the shape display, and takes advantage of the fact that these paths are better rendered by shape displays. The second method, scaling up, renders a scaled-up version of the virtual object onto the shape display, to allow a higher resolution representation of the object. The control to display ratio is then modified to decrease the perceived speed of the finger, creating the illusion that the physical representation is the same size as the smaller virtual object.

We also propose two approaches for increasing the perceived size of the shape display. The first approach, retargeting, allows one shape display to render multiple segments of the virtual environment. The second approach, scaling down, renders a scaled-down version of the virtual object on the shape display, allowing larger objects to be presented. The control to display ratio is then modified to adjust for the mismatch in scale, by altering the scale of the displacement of the finger.

Finally, we suggest two methods for increasing the perceived speed of the actuated pins. The first method is applied when reaching for an object after the movement. In this case, retargeting is used to increase the perceived distance travelled by the pins. When the finger is in contact with the active pins, the second technique uses vertical redirection to increase the perceived speed of the actuated pins. This is achieved by mapping vertical displacements in the virtual world to smaller pin displacements, and decreasing the control to display ratio along the vertical axis.

There are perceptual limits to the use of these visuo-haptic illusions. Beyond a certain threshold, the discrepancy between the visual and tactile sensory input will become too extreme and the brain will reject the illusions [15]. This failure mode is referred to as semantic violation [38]. Previous research has demonstrated the effectiveness of some of these illusions within a small range [4], but the thresholds after which a semantic violation will occur have not been clearly defined. We conduct a study to uncover the limits of the suggested haptic illusions. We then conduct a second study to learn about the effects of these techniques on the perceived performance of shape displays within those boundaries.

Contributions

1. Angle redirection and upscaling for increasing the perceived resolution of shape displays.
2. Retargeting and downscaling for increasing the perceived display size.
3. Retargeting and vertical redirection for increasing the perceived speed of the actuated pins.
4. An evaluation that determines the thresholds for semantic violation of the presented haptic illusion techniques.
5. A second evaluation demonstrating the effectiveness of the presented techniques on the perceived performance of shape displays below the threshold of semantic violation.

RELATED WORK

Encountered-Type Haptics

Encountered-type haptic systems are active devices that move or change shape such that when users make contact with a virtual object, they encounter the haptic device. McNeely introduces the term Robotic Graphics to describe these solutions, and draws an analogy between graphic displays simulating the appearance of an object and a robot simulating its feel [36]. Conventional encountered-type haptic devices are robotic arms with end-effectors that enable rendering of various surface characteristics [48, 18, 1]. In this work, we use shape displays as an encountered-type haptic feedback device in VR to render various 2.5D geometries.

Shape Displays

Shape displays are matrices of actuated pins that can physically render 2.5D content and have been used for a variety of applications including remote collaboration [30, 10], information visualization [49], and Computer-Aided Design [12]. In terms of the design of shape displays there is a trade off between spatial resolution or density, pin travel distance, and actuation speed - mostly tied to actuator choice. A variety of shape displays with different spatial resolutions have been designed. Small tactile pin arrays for single finger contact, commonly with travel of around $1mm$ and higher bandwidths (40-400hz), have been designed using servo motors with linkages [51], piezo bimorphs [47], or shape memory alloys (SMA) [52]. Table top sized displays for interacting with a user's entire hand often have larger travel but less spatial and temporal resolution and have been built using dc motors [19, 33, 12], SMAs [39], or pneumatics [53, 45]. Finally, room scale shape output has been created using hydraulic actuation [16]. However, due to the limitations and cost of actuation technology, to date, there have been few shape displays that have a high spatial and temporal resolution and a large working envelope.

Beyond shape output, researchers have utilized embedded lights or projectors to add visual information to the rendered shape. FEELEX uses a flexible screen on top of the actuated pins to create a dynamic soft surface, on which visual content can be projected [19]. Lumen is an interactive display that employs shape memory alloy to actuate the pins and the color of each pin can be individually controlled to create images, shapes, and physical motions [39]. Shape displays can also be used to provide haptic feedback in mixed reality applications. For example, Sublimate integrates shape displays with augmented reality for rendering spatially co-located 3D graphics [32]. Similarly, in this work we use shape displays as an encountered-type haptic device in virtual reality.

Visuo-haptic illusions

The visual dominance effect is the concept that when senses conflict, vision often dominates. Studies of the conflict between the sense of vision and touch have shown that people often perceive the visual shape instead of the tactual shape, in many cases without even noticing the discrepancy [41, 13]. Pseudo-haptic feedback is a technique in which the real haptic feedback provided is different from the perceived haptic sensation. Pseudo-haptics often uses passive props and primarily takes advantage of the visual dominance effect [26]. This approach has been used to improve the user's perception of contact and to modify the perceived shape, size, texture, and stiffness of passive objects [23, 27]. We apply three visuo-haptic illusions to improve the perceived performance of shape displays: retargeting, redirection, and scaling.

Retargeting

Haptic retargeting is a haptic illusion technique, based on the visual dominance effect, that is applied in cases where the user reaches to touch a virtual object. By utilizing this technique, it is possible to repurpose a single physical object to provide passive haptic sensation for multiple virtual objects [3]. Retargeting can also be used to create a Sparse Haptic Proxy for simulating touch feedback [8]. Three approaches have been introduced for retargeting: world manipulation (modifying the virtual world's coordinate system), body manipulation (modifying the virtual representation of the body parts), and a hybrid technique that combines the two [3]. In these approaches the passive object has to resemble the physical properties of the virtual object perfectly and only the perceived location of the object is modified. We apply this method to shape displays and retarget the finger to increase the perceived size of the interaction space as well as the perceived speed of the pins.

Redirection

Redirection alters the visual representation of the objects and the location of the virtual hand to create various illusions, as the user continuously touches and explores surfaces. Ban et al. modify the visual representation of a passive object and the placement of the virtual hand to create the perception of curvature on flat surfaces [5, 6] or to modify the perceived angle between two parallel lines [4]. Similarly, Kohli uses the boundaries of the physical geometry as a constraint and maps every point on the physical surface to a different virtual surface by warping the virtual space [24]. It is also shown that for some tasks, redirection does not have a negative impact on task performance [25]. We utilize this technique to improve the perceived resolution and speed of shape displays.

C/D ratio

Control to Display (C/D) ratio is the ratio of the real displacement of the users' hand to the displacement of their virtual representation. The modification of the C/D ratio has been used primarily to augment cutaneous haptic feedback for variable stiffness or surface friction [20] - increasing the C/D ratio increases the perceived stiffness and surface friction. C/D ratio has also been used to influence perception of mass [11]. In this work, we use C/D ratio modification as a mechanism for redirection. In particular, we modify the C/D ratio to alter the speed of the finger for scaling and increasing the perceived speed of the actuated pins.

VISUO-HAPTIC ILLUSIONS FOR SHAPE DISPLAYS

We present visuo-haptic illusions for improving the perceived performance of shape displays when used as an encountered-type haptic device in VR by addressing three limitations: low resolution, limited display size, and low pin actuation speed. With the goal of improving the perceived performance of these displays, we propose methods, such as scaling, retargeting, and redirection, for tackling each limitation.

Spatial Resolution

The spatial resolution of a shape display is defined by the distance between its actuated pins [29]. Asamuri et al. suggest that an ideal resolution for a tactile display is half of the Two-Point-Discrimination Threshold (the minimum distance between two points that can be distinguished upon simultaneous contact), which is approximately 1-1.5*mm* for fingertip [2]. Similarly, Shimojo et al. concluded that 3*mm* pins are sufficient for tracing tasks, and that a pin size of 2*mm* or less is required for fingertip interactions [42]. However, given the current cost of actuation technology and size of shape display hardware, achieving such a high resolution, over a large working area, is not practical. The low resolution of current shape displays negatively impacts the smoothness of the rendered surface. In addition, the rasterization of 3D geometries onto the low resolution display limits the complexity of the content that can be physically presented. To address this limitation, we suggest two approaches: linear redirection of edges and scaling up from the virtual world to the real word, using C/D ratio modification.

Angle Redirection

In order to improve the perceived resolution of the display, we need to consider how people perceive shapes when engaging in active touch; an exploratory sense that reveals many properties of the environment and surrounding objects [14]. Studying how individuals touch physical objects has led to a better understanding of different types of exploratory procedures, which include lateral motion associated with texture, unsupported holding associated with weight, enclosure associated with size, contour following for shape extraction, pressure associated with surface stiffness, and static contact associated with temperature [22]. In this section, we focus on contour following for shape extraction.

For a shape display laid out on a 2D xz Cartesian grid, horizontal and vertical edges can be well represented. However, aliasing occurs when rendering edges that are positioned at an angle. Since anti-aliasing is not easily possible with the sense of touch, we propose a redirection technique that maps a line positioned at an angle in the virtual world to a horizontal or a vertical path on the physical shape display. For example, by redirecting the virtual representation of the finger, while following a horizontal path on the shape display (shown in Figure 2a) the user perceives a sloped edge (shown in Figure 2b). For this example, with the assumption that the user's finger is traversing the shape display along the x-axis and that redirection occurs along the z-axis, the finger displacement Δz can be calculated by

$$\Delta z = \Delta x \times \tan \alpha \quad (1)$$

where α is the redirection angle between the virtual line and the x-axis and Δx is the distance between the current position of the finger and the beginning of the redirected path. Modifying the position of the virtual finger by Δz creates the illusion of following a sloped edge. Note that we only apply redirection to modify the angle of linear paths; however, it has been shown that a similar approach can be taken to imply curvature when following linear paths [5].

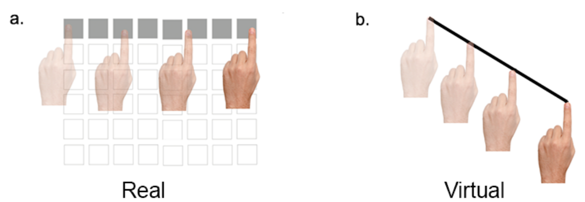

Figure 2. (a) User's hand moving from left to right on the shape display. (b) Virtual hand redirected at an angle.

Scaling Up

We propose another approach for improving the perceived resolution of shape displays by upscaling virtual objects on to the shape display. Mapping small virtual objects to larger physical renderings, allows the shape display to represent complex content with higher resolution and to render details that are perceived to be smaller than the size of the individual pins. To correct for the mismatch of scale, the C/D ratio is increased such that the real distance traveled (shown in Figure 3a) is larger than the virtual distance travelled (shown in Figure 3b).

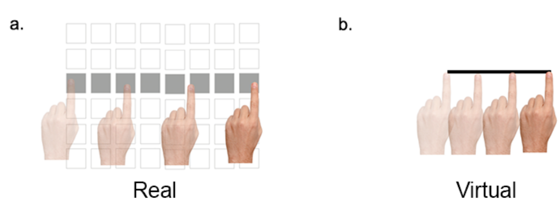

Figure 3. (a) User's hand moving from left to right on the shape display. (b) Virtual hand displacement scaled up on the shape display to improve resolution.

Shape Display Size

The cost and complexity associated with adding more pins limits the size of the shape display, ultimately constraining the interaction area for which haptic feedback can be provided. To tackle this problem we suggest two approaches: retargeting for mapping one shape display to multiple areas in the virtual space, and scaling down from the virtual world to the real world for increasing the perceived size of the display.

Retargeting

Retargeting can be used to increase the perceived size of the shape display. Similar to the approach taken for repurposing passive haptic objects [3], a hybrid technique, combining world warping and body warping, is used to render the area that is being haptically explored by the user. Each time the user approaches a virtual object, the perceived location of the virtual object is mapped to the location of the shape display, and the display reforms in order to physically render that virtual object. The disadvantage of this method is that a continuous surface cannot be provided and upon making contact with a virtual object, the interaction space becomes constrained by the size of the shape display. This can be indicated to the user by highlighting the current working envelope.

Scaling Down

Another method for increasing the interaction space is scaling down from the virtual environment. In this case the C/D ratio is reduced so that the real distance travelled (shown in Figure 4a) is smaller than the virtual displacement of the finger (shown in Figure 4b). This approach allows rendering of larger virtual objects and increases the perceived size of the display; however, as a side effect, the display resolution is reduced.

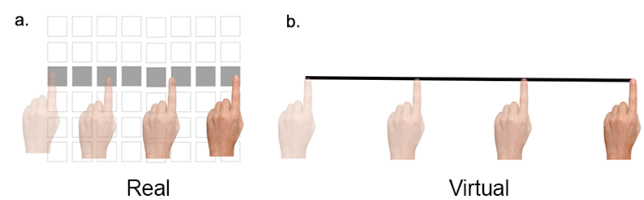

Figure 4. (a) User's hand moving from left to right on the shape display. (b) Virtual hand displacement scaled down on the shape display to increase display size.

Pin Speed

Shape displays consist of actuated pins that move vertically, allowing the display to morph into a variety of shapes. In addition to rendering multiple virtual objects, shape displays are capable of representing movements and deformations of virtual elements. In this case, as users haptically explore an object, the pins can move up or down to render the movement of that object in real-time. The speed of the actuated pins, however, limits the rate at which the display can change shape. We suggests two methods to address this limitation: retargeting and vertical redirection.

Retargeting

When reaching for an object after the movement, retargeting can be used to increase the perceived speed of the display. In this case body warping [3] is used to create the illusion that during the movement the pins have travelled a larger distance from their original position. The finger is retargeted to touch the pins on the shape display, while the virtual finger makes contact with the virtual object at a higher position.

Vertical Redirection

For the case where fingers are in contact with the display, we increase the perceived speed of the pins, by decreasing the C/D ratio such that the distance travelled by the pin is smaller than the displacement of the virtual object. For example, during a time interval Δt, the distance travelled by the actuated pin Δy can be calculated using

$$\Delta y = \frac{\Delta y'}{1 + \frac{\gamma}{100}} \tag{2}$$

where $\Delta y'$ is the displacement of the virtual object at that location, and γ is the percentage increase in speed from the real world to the virtual world.

EVALUATIONS

We designed two studies to evaluate the suggested interventions. The first study determines the threshold below which haptic illusions do not result in a semantic violation; a failure caused by large discrepancies between visual and tactile sensory input [38]. The results of the first experiment were then used to define the ranges for the second study, conducted to gain some understanding of the outcome of each intervention. The focus of both evaluations is on the effect of redirection and upscaling on the perceived resolution of the shape display, and the impact of vertical redirection on the perceived speed of the pins. Retargeting and down scaling for increasing the display size are not included in this evaluation, as they are previously studied on passive haptic objects [3, 8, 27, 23] and can be directly applied to shape displays.

EVALUATION 1: BOUNDARIES OF HAPTIC ILLUSIONS

The first study determines the threshold of haptic illusions that do not result in a semantic violation. Previously, the effectiveness of these illusions have been demonstrated within a narrow range [4], but the limits have not been clearly defined.

Participants

19 right-handed participants were recruited (12 female and 7 male), ages 19 to 29 (mean = 22). 14 participants had experienced virtual reality prior to the experiment. Each person received a $15 gift card for their participation in the study.

Experimental Setup

For the first evaluation, we were interested in understanding the limits of visuo-haptic illusions independent from the shape display. Therefore, for studying the effects of redirection and scaling up, we used a passive device that consisted of a 3D printed rod placed on a removable plate. The experimenter could modify the angle of the rod by rotating and snapping the end point, and the length could be altered by sliding the end point along the rod. To ensure that the findings of this study could be applied to the active shape display that we used for our applications (ShapeShift [43]), we set the maximum length of the rod to be 90*mm*; the width of our shape display. In addition, a single linear actuator (TTMotors TGPP06, 1:25, 6*mm*), identical to those used in our shape display, was used for studying the perception of the speed of the pins.

The apparatus, as shown in Figure 5, consisted of the passive device, a Head-Mounted Display (HMD), noise cancelling headphones, motion capture cameras, and retro-reflective markers. In order to track the participants' finger in real-time, we attached a 3D printed marker holder with retro-reflective markers to their index finger with medical tape, which enabled a more reliable tracking. Retro-reflective markers were also attached to the shape display and the HMD. The OptiTrack motion capture cameras tracked these rigid bodies and the position and orientation data was streamed using Motive optical motion capture software to the Unity3D game engine. The Oculus Rift HMD was then used to present the virtual reality content to the user.

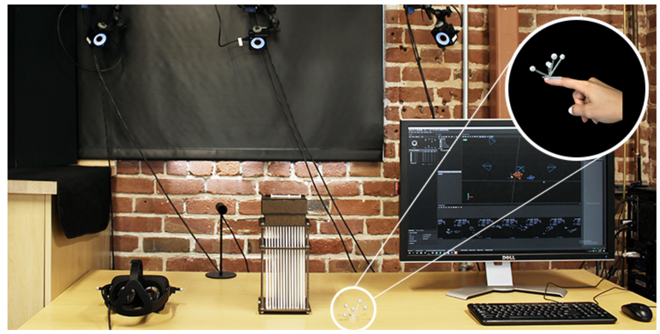

Figure 5. The experimental setup consisting of the VR head-mounted display, motion capture system, and retro-reflective finger markers.

Procedure

We used the method of constant stimuli to determine the detection threshold for each visuo-haptic illusion. The participants were informed about the use of illusions and the goal of this study. The study consisted of 3 parts, one for each technique, the order of which was randomized. First, the finger marker was attached to the participants' index finger, using medical tape. Then, participants wore the HMD and the noise cancelling headphones. White noise was played through the headphones to avoid distractions and to eliminate the audio cues that may have revealed the haptic illusions.

At the beginning of each of the 3 parts, participants had a short training session in which they haptically explored two objects, one without an illusion and the other with an illusion that was easy to detect and far beyond the limits of semantic violation. This was done so that participants could experience each type of illusion, prior to the study. After the training, participants were presented with multiple virtual objects and these samples were randomized. The boundaries and the step sizes were chosen based on the results of the pilot studies.

Participants were asked to slowly explore the surface of each virtual object with the tip of their index finger. They were told to hold their hand in a pointing position and to avoid touching the rest of the setup. No time constraints were given during this exploration process. Based on a prior study design [35], we asked the following questions at the end of every sample:

1. Was there an illusion? Yes or no?
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.

Overall 60 samples were evaluated. The study was an hour-long, including two 5-minute breaks after each part. At the end of the study, the Simulation Sickness Questionnaire (SSQ) [21] was used to evaluate the effects of the visuo-haptic illusions on the physical state of the participant.

Part 1: Redirection for Increasing the Resolution

The first part evaluated the limits of redirection when mapping slanted lines to horizontal lines. Instead of placing the rod at an angle (as shown in Figure 6b), the rod was placed horizontally (as shown in Figure 6a) and redirection was used to create the illusion of the finger following a slanted line in VR.

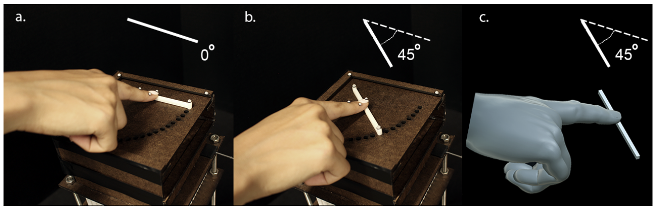

Figure 6. (a) Redirection of the 45° line onto a horizontal line. (b) Line placed at 45° with no illusion. (c) The visual feedback in both scenarios.

We tested 5 angles: 5°, 15°, 25°, 35°, and 45°. Each sample was repeated 4 times for a total of 20 samples. The physical representation of each angle is shown in Figure 7. Note that during the study, for all samples, the physical rod was placed horizontally and only the angle of the virtual rod was modified.

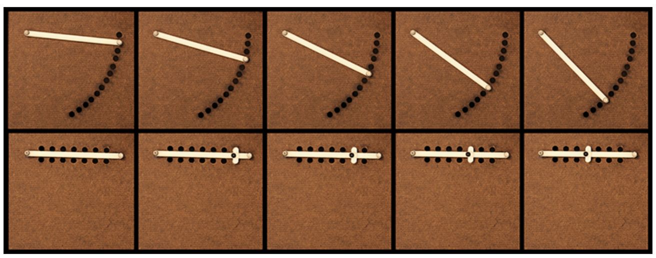

Figure 7. Top: all angles evaluated at 5°, 15°, 25°, 35°, and 45°. Bottom: all scale factors evaluated at 1x, 1.14x, 1.33x, 1.6x, and 2x.

Part 2: Scaling Up for Increasing the Resolution

The second part evaluated the limits of scaling up. Based on the pilot studies we determined the potential boundaries for the scale factors. The smallest scale factor was 1x with no illusion, and the largest scale factor was 2x when scaling up a 45*mm* virtual rod onto a 90*mm* physical rod. We then divided the distance between these two points into 4 equal pieces, resulting in the following 5 scale factors: 1x, 1.14x, 1.33x, 1.6x, and 2x. Each sample was repeated 4 times for a total of 20 samples. Each length is shown in Figure 7. Note that during the study, for all samples, the physical rod was 90*mm* long and only the virtual length of the rod was modified.

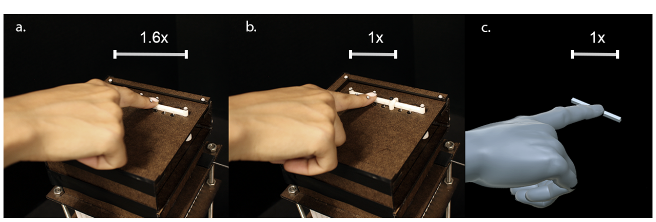

Figure 8. (a) Line scaled up by a factor of 1.6x. (b) Line at 1x scale with no illusion. (c) The visual feedback in both scenarios.

Part 3: Increasing the Perceived Pin Speed

In the third part, we studied the limits of vertical redirection using one actuated pin. At every sample, the participant's finger was placed on top of the pin, as shown in Figure 9. The physical pin travelled a total distance of 50mm at 60mm/s. The perceived speed was altered by increasing the virtual distance travelled by the pin. The virtual finger was then redirected to match the position of the virtual pin. The limits of this haptic illusion had a high variance among the pilot study participants and the boundaries were unclear. For this reason, unlike the first two parts in which we used a linear sampling, we doubled the speed increase at every step. We evaluated 5 speed increases: 25%, 50%, 100%, 200%, and 400%. These led to 5 samples with speed up factors of 1.25, 1.5, 2, 3, and 5. Each sample was repeated 4 times for a total of 20 samples.

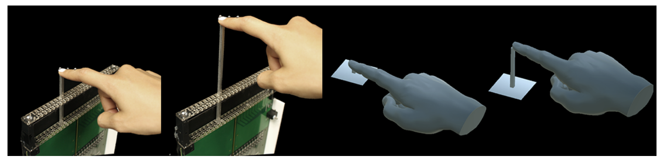

Figure 9. Pin moving up and the corresponding virtual scene.

Results and Discussion

We calculated the detection ratio for each person at every sample point, by finding the ratio of the number of times an illusion was detected for that sample, divided by the total number of repetitions of that sample. Illusion was detected when the participant would state that there is an illusion with a confidence level of 3 or higher. We then averaged the detection ratios across participants for each sample and plotted the results. We fitted a psychometric function of the form

$$f(x) = \frac{1}{1+e^{ax+b}} \tag{3}$$

with real numbers a and b [46]. The Conservative Detection Threshold (CDT) or point of subjective equality is defined as the value corresponding to the average detection ratio of 0.5. Values below the CDT are likely to not have been detected by participants, as a random guess would have results in an average detection ratio of 0.5. Based on previous literature [35, 46] we choose the value corresponding to an average detection ratio of 0.75 as the Detection Threshold (DT). Note that in all figures the error bars correspond to the 95% bootstrap confidence intervals.

In part 1 we used redirection to map angled lines to horizontal lines. For this illusion, we found the detection threshold to be 49.5°, as shown in Figure 10, for a psychometric fit with parameters $a = -0.0804$ and $b = 2.88$. In part 2 we investigated scaling up as a means of improving the perceived resolution of the display. For this illusion, we found the detection threshold to be at a scale factor of 1.90x, as shown in Figure 11, for a psychometric fit with parameters $a = -3.00$ and $b = 4.59$. In part 3 we studied the illusion of vertical redirection. For this technique, we found the detection threshold to be at a 3.29x speed increase, as shown in Figure 12, for a psychometric fit with parameters $a = -1.67$ and $b = 4.39$.[1]

In part 2, we modified the C/D ratio on the xz-plane as the participant explored the surface of the virtual hemisphere. In part

[1]Experiment data for both studies can be found at `https://shape.stanford.edu/research/hapticIllusions/data.xlsx`

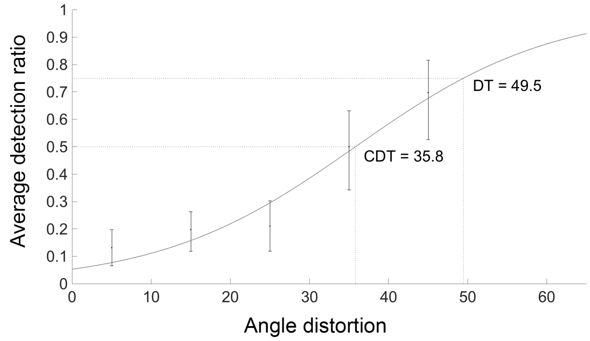

Figure 10. Average detection ratio versus angle distortion graph. Detection threshold is at 49.5°.

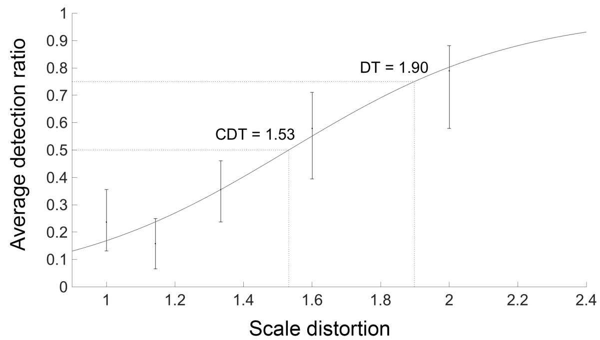

Figure 11. Average detection ratio versus scale factor distortion graph. Detection threshold is at 1.9x scaling factor.

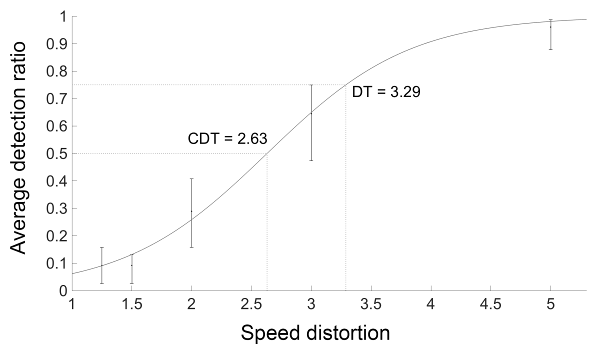

Figure 12. Average detection ratio versus speed distortion graph. Detection threshold is at 3.29 speed up.

3, we modified the C/D ratio along the y-axis as the pin moved the participant's finger up. It is interesting to note that the DT for speed distortion was 1.7x higher than the DT for scale distortion. We hypothesize that participants are more sensitive to distortion when initiating the movement and exploring the surface of an object, in comparison to passively following the object's movement. Another possible explanation is that distortions along a horizontal plain may be easier to detect compared to vertical distortions.

The Total Severity (TS) score calculated from the SSQ questionnaire was 44.9. We hypothesize that this high TS score is related to the semantic violation, as we went beyond the limits of visuo-haptic illusions. The high temperature in the lab and participants' standing position may have also contributed to the simulation sickness. We took these hypotheses into consideration when designing the second evaluation.

EVALUATION 2: AFFECTS OF PROPOSED ILLUSIONS

The second study was designed to understand the effects of each intervention on the perceived performance of shape displays. To prevent semantic violation, we used the detection thresholds (DT) found in the first experiment to define the boundaries for this study.

Participants

19 right-handed participants were recruited (8 female and 11 male), ages 22 to 57 (mean = 35). 15 participants had experienced virtual reality prior to the experiment. Note that there was no overlap between the participants of the two studies. Each person received a $15 gift card for their time.

Experimental Setup

For the second study, we chose not to use our shape display [43] because a few pins were not consistently functional. We found in the pilot studies that even when one pin malfunctioned, the perception of resolution was negatively affected. Since we could not guarantee that the display would render objects perfectly at every sample, we used a passive device. The device consisted of a platform and a set of removable top plates. A 3D printed 12×24 gird of $4.85mm \times 4.85mm$ pins, with an inter-pin spacing of $2.8mm$, similar in resolution to the shape display, was placed on each plate to "render" different objects. In addition, a single linear actuator (TTMotors TGPP06, 1:25, $6mm$), identical to those used in our shape display, was used for studying the perception of the speed of the pins. The rest of the apparatus was similar to the first study, consisting of the HMD, noise cancelling headphones, motion capture cameras, and retro-reflective markers.

Procedure

For this study, based on previous literature [46, 28, 50], we used the method of constant stimuli in a two-alternative forced-choice (2AFC) task. The study consisted of 3 parts, one for each technique, the order of which was randomly selected. In each part, we presented participants with multiple randomized trials. Each trial consisted of two samples, one rendering the virtual object without an illusion and the other with the use of visuo-haptic illusions. The order of the two samples within each trial was also randomized. The participants were not aware of the use of visuo-haptic illusions and the goal of the study. Instead, they were told that the study is designed to compare the performance of different shape displays. The passive device and the actuated pin used in the study were not shown to the user. The participants only saw a video of a shape display and the concepts of resolution and speed were described to them.

First, the finger marker was attached to the participants' index finger, using medical tape. Then, participants wore the HMD and the noise cancelling headphones. White noise was played through the headphones to avoid distractions and to eliminate the audio cues that may have revealed the haptic illusions. At the beginning of each part, participants had a short training session in which they tried one sample and explored the surface of the virtual object used in that part. The range of samples were chosen based on the detection thresholds found in the first study. Similar to the previous study, they were asked to slowly explore the surface of each virtual object with the tip of their index finger. No time constraints were given during this exploration process.

For each part of the study, 4 distortion levels were tested. These intervals were chosen based on pilot studies to be roughly evenly spaced and below the minimum detectable change in angle, scale factor, and speed increase. Overall 24 pairs of samples were evaluated. The study was an hour-long, including two 5-minute breaks after each part. At the end of the study, the Simulation Sickness Questionnaire (SSQ) [21] was used to evaluate the effects of the visuo-haptic illusions on the physical state of the participant.

Part 1: Redirection for Increasing the Resolution

The first part studied the effects of angle redirection on the perceived resolution of the display. As shown in Figure 13, instead of rendering a line at an angle, the passive device "rendered" a horizontal line and redirection was used to create the illusion that the finger was following the slanted line.

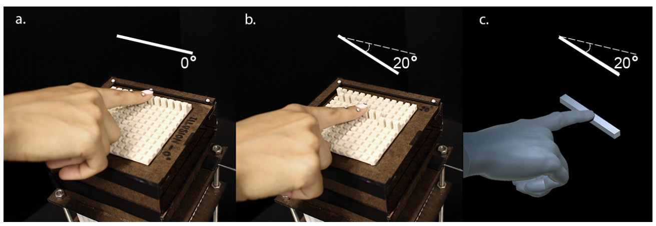

Figure 13. (a) Redirection of the 20° line onto a horizontal line. (b) Line placed at 20° with no illusion. (c) The visual feedback in both scenarios.

We tested 4 angles: 10°, 20°, 30° and 40°. We used 40° as the upper bound based on the DT found in study 1. We chose three points below this threshold to obtain a distribution. Each trial was repeated twice for a total of 8 trials or 8 pairs of samples. The 3D printed plated are shown in Figure 14.

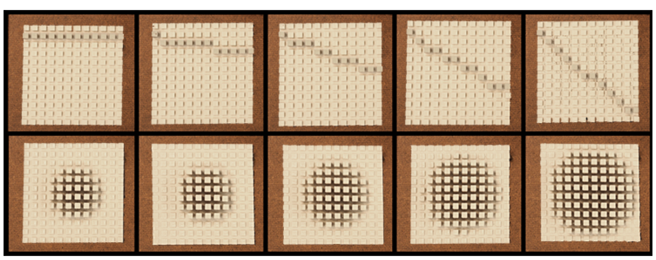

Figure 14. Top: the horizontal line used for redirection and all angles evaluated at 10°, 20°, 30°, and 40°. Bottom: the hemisphere with no scaling as well as all scale factors evaluated at 1.2x, 1.4x, 1.6x, and 1.8x.

At every trial the original rendering of the angled line was compared to the horizontal line with redirection, and the following three questions were asked:

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

Part 2: Scaling Up for Increasing the Resolution

The second part evaluated the effect of scaling up on the perceived resolution of the display. As shown in Figure 15, instead of rendering a hemisphere, the passive device "rendered" a scaled up version of the hemisphere and C/D ratio modification was used to match the scale of the physical representation with the virtual object.

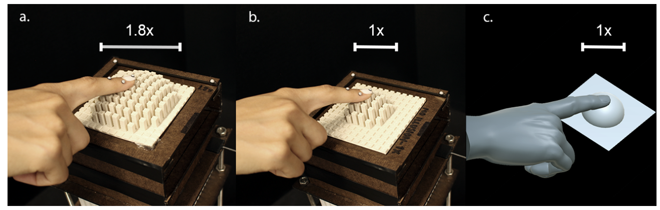

Figure 15. (a) Hemisphere scaled up by 1.8x. (b) Hemisphere at 1x scale with no illusion. (c) The visual feedback in both scenarios.

We tested 4 scale factors: 1.2x, 1.4x, 1.6x, and 1.8x. We used 1.8x as an upper bound based on the DT found in study 1, and chose three points below this threshold to obtain a distribution. Each trial was repeated twice for a total of 8 pairs of samples. The 3D printed plates are shown in Figure 14. At every trial the original rendering of the hemisphere was compared to the scaled up hemisphere with C/D ratio modification, and the same questions as part 1 were asked.

Part 3: Increasing the Perceived Pin Speed

In the third part, we studied the effects of vertical redirection on the perceived speed of the pin. Similar to study 1, we used one actuated pin that travelled a total distance of $50mm$ at $60mm/s$. We tested 4 speed increases: 1.5x, 2x, 2.5x, and 3x, by modifying the distance travelled by the virtual pin and the virtual finger. We used 3x as an upper bound based on the DT found in study 1, and chose three points below this threshold to obtain a distribution. Each trial was repeated twice for a total of 8 trials or 8 pairs of samples. At every trial the speed of the physical pin, shown on the left in Figure 16, was compared to the sped up version with vertical redirection, shown on the right. At the end of every trial the experimenter asked: which display did you think was faster? 1 or 2?

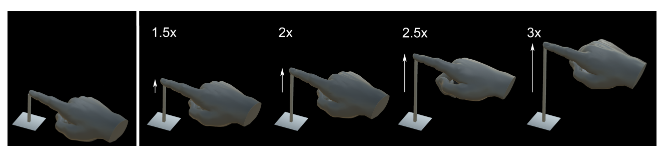

Figure 16. The pin at maximum height with no illusion and all perceived speed increases evaluated at 1.5x, 2x, 2.5x, and 3x.

Results and Discussion

For part 1 and 2, we calculated the percentage of responses in which the sample with illusion was selected as higher resolution, smoother, and the one that participants prefer. The results for part 1 (angle redirection) are shown in Figure 17. All percentages are above 81% which suggests that below the limits of semantic violation, regardless of the angle, redirecting slanted lines onto horizontal lines is an effective way of increasing the perceived resolution and smoothness of the display. The samples that had an illusion were also preferred by participants. However, note that the participants' preference may have been influenced by the two questions asked earlier about the resolution and smoothness of the display. In all figures the error bars correspond to the 95% bootstrap confidence intervals.

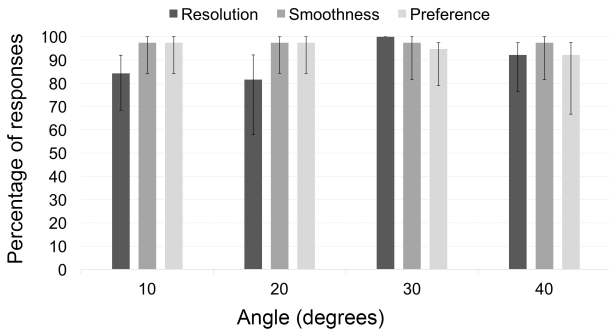

Figure 17. The percentage of responses in which the sample with illusion was perceived as higher resolution, smoother, and the one they prefer.

The results for part 2 (scaling up) are shown in Figure 18. All percentages were above 63%, which is higher than the point of subjective equality at 50% for a 2AFC task [46]; this is the threshold after which the participants' selections are not by chance. At 1.8x scale factor, 92% of participants selected the scaled up sample as higher resolution, smoother, and the one that they prefer.

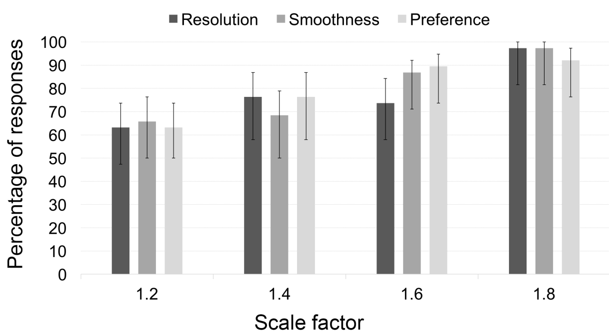

Figure 18. The percentage of responses in which the sample with illusion was perceived as higher resolution, smoother, and the one they prefer.

The results for part 3 (vertical redirection) are shown in Figure 19. All percentages are above 73% suggesting that below the limits of semantic violation, vertical redirection can be used to increase the perceived speed of the pins.

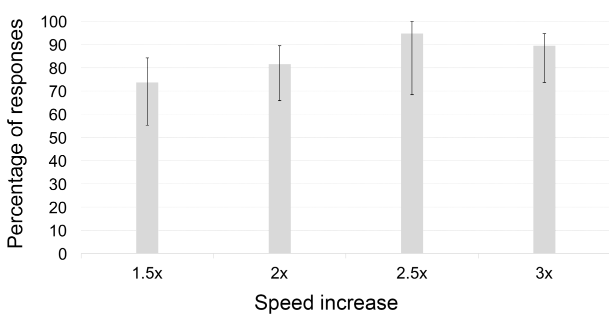

Figure 19. The percentage of responses in which the sample with illusion was perceived to be faster for each speed increase.

The results for part 1 show that angle redirection is effective for all angles. This illusion acts as an anti-aliasing mechanism, improving the perceived resolution and smoothness of all slanted lines below the DT. In contrast, scaling up and speed increase may be more effective at higher distortion levels, as the effects of smaller changes remain unnoticed by some participants. For example, a higher percentage of participants perceived the sample with illusion at 1.8x scale factor as higher resolution, smoother, and the one they prefer, compared to the sample at 1.2x scale factor.

The answers to the SSQ questionnaires suggest that the haptic illusions did not result in significant motion sickness — Total Severity score was 15.0.

APPLICATIONS

We developed three applications, using ShapeShift [43], to demonstrate the techniques suggested for improving the perceived performance of shape displays. The first application, pentagon maze, uses redirection to map slanted paths of a maze to horizontal and vertical lines in real-time. The virtual museum example showcases how scaling up can improve the perceived resolution of the display when rendering a relief piece. Finally, the bouncing ball example demonstrates how vertical redirection can improve the perceived speed of the actuated pins.

Pentagon Maze

The first application is a pentagon maze. The shape display renders the walls of the maze, providing haptic feedback as the user's finger follows the path. As shown in Figure 20, when rendering these slanted walls aliasing results in an uneven surface, making it difficult and unpleasant to follow the path on the maze.

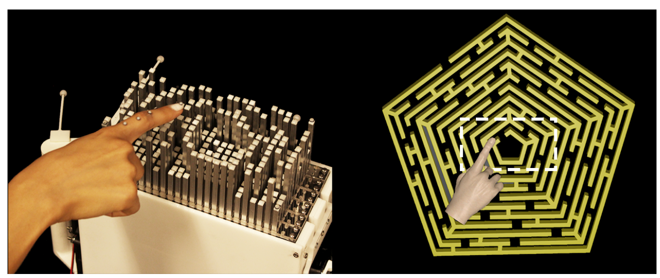

Figure 20. Pentagon maze rendered on the shape display.

We use redirection to improve the perceived resolution of the display. As the user follows the path, the shape display renders horizontal and vertical paths in real-time (Figure 21). Redirection is then used to create the illusion that the user's finger is following the slanted walls of the maze. Note that the current prototype does not work continuously over the entire maze. Users can only explore the area marked with a rectangle in Figure 21. Once the user removes their finger, retargeting can be used to render different sections of the maze.

Virtual Museum

The second application is a virtual museum displaying artifacts from ancient Greece and Rome. The advantage of the virtual museum is that visitors can haptically explore the art work. In this example, the shape display renders a segment of a sculpted relief piece that is of interest to the user. Due to the low resolution of the display, the shape display cannot represent the details of the piece and the rendered surface is uneven (as shown in Figure 22a). To improve the perceived resolution of the display and to create a smoother surface,

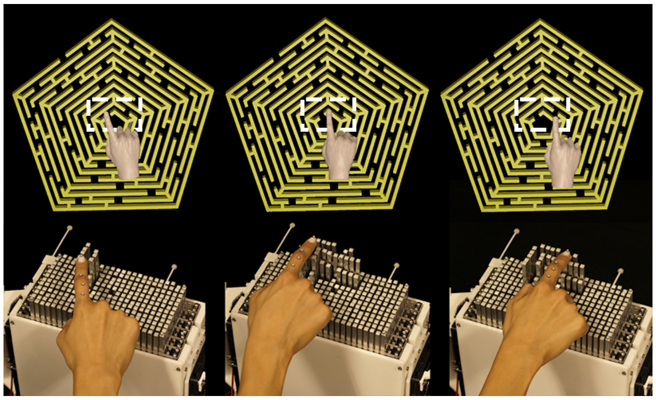

Figure 21. Vertical and horizontal paths are rendered on the shape display in real-time as the user's hand traces the maze. Redirection is used to create the illusion that the hand is tracing paths at different angles.

the area of interest is scaled up onto the shape display. Note that this illusion reduces the working area, as shown by the inner rectangle on the virtual scene in Figure 22b. Once the users' finger reaches the boundaries of the physically rendered surface, they need to remove their finger and retargeting can be used to render a different section of the artifact.

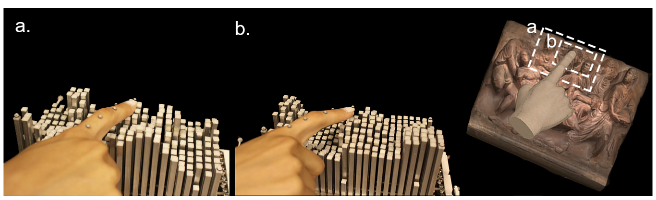

Figure 22. The surfaces of the sculpted relief is scaled up onto the shape display by a factor of 1.8x to create a smoother and higher resolution representation. The original rendering of the piece is shown on the left.

Bouncing Ball

In this example, the bouncing ball travels faster than the maximum speed of the display. Due to this limitation, when the user's finger is placed on top of the bouncing ball, the virtual finger will not travel at the same speed as the virtual ball. To increase the perceived speed of the actuated pins, we use vertical redirection to match the position of the virtual hand to the position of the virtual ball during the movement.

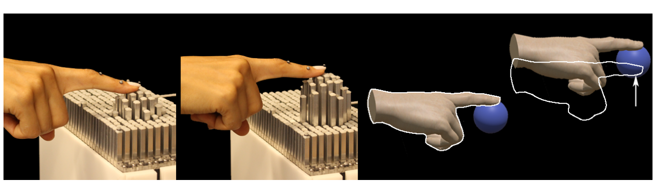

Figure 23. The virtual bouncing ball moves 3x faster than the maximum speed of the display. Vertical redirection is used to increase the perceived speed of the virtual hand.

LIMITATIONS & FUTURE WORK

In this work, all exploratory procedures are limited to single finger interactions. This limitation stems from the fact that a reliable and high precision hand-tracking system was not available. Full hand tracking will enable new forms of exploratory procedures, such as enclosure for extracting the size of the virtual objects [22]; however, it will also introduce new challenges when applying visuo-haptic illusions, such as maintaining kinematic constraints. Future work should explore how the same concepts can be adapted and applied when more than one finger is used for haptic exploration. Moreover, for real-time applications, prediction algorithms are needed to find the segment of the virtual environment that is more likely to be touched.

The findings of the two evaluations are dependent on the size and resolution of the shape display. For example, in the first study, having a larger display might lower the detection threshold for redirection of slanted edges. Future work should consider decoupling visuo-haptic illusions from specific shape display hardware. Moreover, scaling up for increasing the perceived resolution of the display, is dependent on the size of the pins as well as the details on the surface of the virtual object. This is an interesting rasterization problem that can be studied to determine the optimal scale factor based on the details of the virtual object and the shape display specifications.

Some of the techniques presented in this work have inherent limitations. For example, scaling down for increasing the perceived size of the display reduces the perceived resolution, and scaling up for increasing the perceived resolution of the display reduces the working area. To mitigate these effects and to improve the overall performance of shape displays as haptic feedback devices, multiple visuo-haptic illusions need to be employed simultaneously. Since we have only evaluated the effects of each intervention independently, it is necessary to better understand the interdependency between these techniques.

Finally, in this work we have applied haptic illusion techniques to a matrix of actuated pins; however, these techniques can be generalized and applied to other forms of shape-changing displays, such as pneumatically actuated displays. Future work should investigate how these techniques can be adapted for improving the perceived performance of other forms of shape-changing interfaces.

CONCLUSION

Shape displays can provide realistic haptic feedback in virtual reality, however the low resolution, small display size, and the low pin speed of these devices limit their usage. Visuo-haptic illusions such as scaling, retargeting, and redirection can be utilized to address these limitations and improve the perceived performance of shape displays. We suggest two methods, angle redirection and upscaling, for improving the perceived resolution of shape displays. We also propose two approaches, retargeting and downscaling, for increasing the perceived size of the display. Finally, we increase the perceived speed of the pins by retargeting and vertical redirection. The results of our evaluation suggest that redirecting sloped lines with angles less than 40° onto a horizontal line, and scaling up to $1.8x$ are effective techniques for increasing the perceived resolution of the display. Moreover, a $3x$ perceived speed increase can be achieved by vertical redirection and modifying the C/D ratio.

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