Effects of Tactile Feedback on the Perception of Virtual Shapes on Non-Planar DisplayObjects

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ABSTRACT
In this paper, we report on a study investigating a novel haptic illusion for altering the perception of 3D shapes using a non-planar screen and vibrotactile friction. In our study, we presented an image of a rectangular prism on a cylindrical and a flat display. Participants were asked to move their index finger horizontally along the surface of the displays towards the edge of the rectangular prism. Participants were asked whether they were experiencing a flat, cylindrical or rectangular shape. In one condition, a vibrotactile stimulus simulated increasing friction towards the visible edge of the rectangular prism, with a sudden drop-off when this edge was crossed by the finger. Results suggest that presenting an image of a rectangular prism, and applying vibrotactile friction, particularly on a cylindrical display, significantly increased participant ratings stating that they were experiencing a physical rectangular shape.

Author Keywords
Organic User Interfaces; DisplayObjects; Shaped Displays; Vibrotactile Feedback.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
According to Ernst et al. [9], when assessing the physical properties of objects, users combine visual and haptic information in an integral way. This allows users to not just assess visual affordances of the object, but also physical properties such shape, weight, weight distribution, temperature, texture and other material properties. Such haptic properties are sensed through receptors in the skin of the fingertips as well as by mechanoreceptors in muscle, tendons and joints that provide kinesthetic feedback [23]. While there has been a substantial amount of work performed on the simulation of kinesthetic properties in Virtual Reality systems [31,12,18] and vibrotactile [13] and electrovibration [4] cues on flat surface displays, little attention has been paid to the perception of shape using non-planar displays such as DisplayObjects [1]. DisplayObjects are a type of Organic User Interface (OUI) [14] consisting of a rigid 3D shaped object covered in a seamless interactive display. Because they are physically three-dimensional, DisplayObjects inherently provide the user with kinesthetic feedback that is richer than that of traditional flat displays. When touching a cylindrical display, for instance, the user's arm and wrist need to move in three dimensions to allow the fingers to touch the front, sides and back surface of the DisplayObject. This generates the kinesthetic perception of real volume.

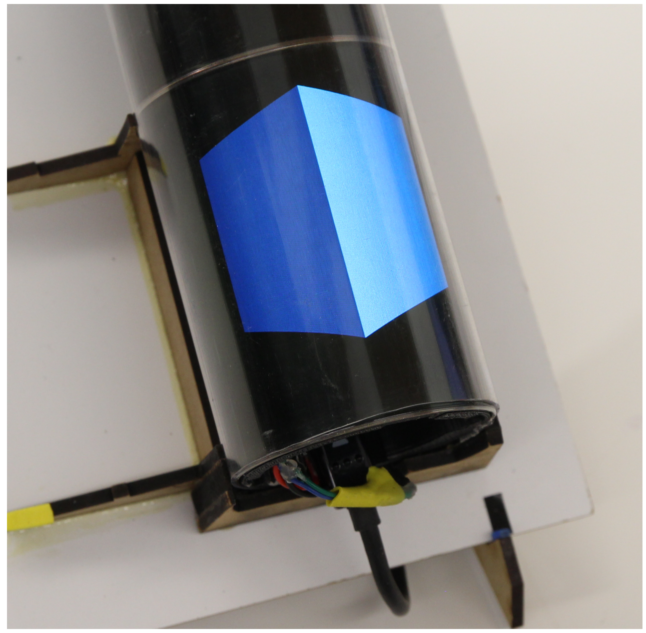

Figure 1. Cylindrical DisplayObject with rectangular prism image.

In this note, we explore an experiment modulating the perception of shape via three mechanisms: shape of display, 3D image shape and vibrotactile friction feedback. Results suggest that the interaction of kinesthetic feedback provided by a cylindrical display, an adequately designed vibrotactile feedback signal, and an image corresponding to a prism shape, allows for the simulation of touching the corner of a virtual rectangular prism when touched with one finger.

CHI 2017, May 06-11, 2017, Denver, CO, USA
© 2017 ACM. ISBN 978-1-4503-4655-9/17/05...$15.00
DOI: http://dx.doi.org/10.1145/3025453.3025488

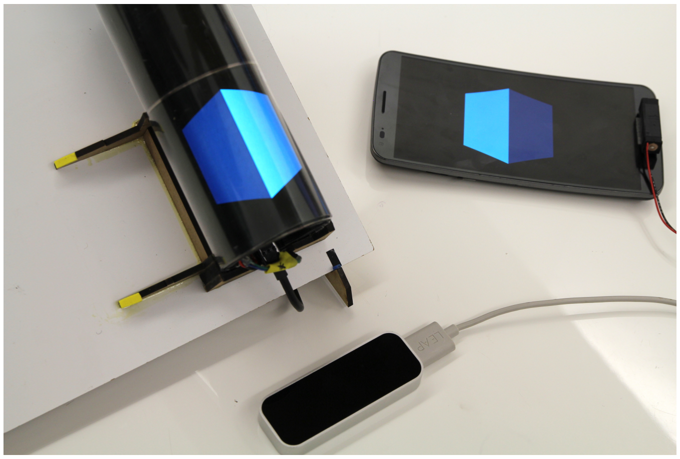

Figure 2. Apparatus used in the study: Cylindrical display (left), Flat display (right), and Leap Motion (bottom).

RELATED WORK

We first discuss work on haptic feedback in user interfaces, after which we briefly discuss a selection of relevant haptics research.

Haptic Feedback in User Interfaces

Despite touch screens being dominant in the mobile design space today, the haptic experience of flat surfaces is different from the rich haptic cues provided by everyday objects [5,13]. To solve this problem, the use of mechanical or electric vibration to simulate the feeling of touching GUI widgets [13] or textures [4] has been proposed. However, these solutions are only capable of creating tactile stimuli, leaving the kinesthetic channel largely underexplored. A frequent alternative are *force feedback* devices [24,31]. These have the disadvantage of being frequently de-coupled from the display output. Some HCI researchers have proposed the use of shape changing displays, often implemented as 2.5D interactive surfaces [10]. This approach, with a few exceptions [15], requires complex electromechanical tabletop platforms not adequate for mobile applications. Some recent research has shown that the combination of shape-changing mobile devices with vibrotactile feedback [33] has potential for conveying rich haptic experiences. Displays with complex shapes are, however, still difficult to build. Poupyrev et al. [28] studied interaction possibilities with multifaceted displays. They used actual polyhedric objects for input, but they had to simulate output by means of 3D models. Stavness et al. [32] proposed a simpler cubical display with perspective correction. Their pCubee used multiple small off-the-shelf displays. A problem with this approach is the presence of bezels that interrupt a continuous view. We made use of recent advances in Flexible Organic LED (FOLED) displays to create a cylindrical DisplayObject. In the past, cylindrical displays have been proposed for teleconferencing [17], public display applications [6], hand scroll emulation for text display [27], and gaming [30].

Haptic Illusions and Shape

Haptic illusions, a phenomenon widely studied by cognitive psychologists [21], can be used for simulating haptic qualities for virtual objects. According to Lederman et al. [23], geometric properties of objects generally comprise shape and size. Lederman et al. [22] observed that the assessment of shape in humans is conducted using *exploratory procedures*. These are a stereotyped pattern of manual exploration observed when people are asked to learn about a particular object property during voluntary manual exploration with or without vision. Of these procedures, contour following is used to determine the exact shape of an object. Objects that fit to the fingertip reveal shape by skin indentation. Curvature has received particular attention in the literature: when the finger presses against a curved surface, responses of slowly adapting mechanoreceptors are directly mapped to the pressure gradient on the skin [11]. Principal material properties of objects comprise surface texture, compliance, and thermal quality. Perceived surface texture might be characterized in terms of its roughness, stickiness, slipperiness, or friction. By constraining exploratory procedures associated with these properties it is possible to induce haptic illusions. E.g., Kildal [16] created the illusion of surface compliance by altering the perceived friction of a virtual button through modulation of the amplitude and frequency of vibrations. Dostmohamed et al. [8] found that it is possible to recreate the sensation of touching a curved surface simply by rotating a flat platform around a static finger. Another way to induce haptic illusions is by sensory substitution. Prattichizzo et al. [29] used a device that compresses the fingerpads, successfully providing a full haptic experience in absence of kinesthetic feedback.

Lécuyer el al. surveyed research work that exploited the dominance of the visual channel to create multiple haptic illusions [19]. For instance, Lécuyer et al. [20] observed that visual feedback can induce the sensation of haptic feedback in isometric input devices. More recently, Ban et al. [3] used image processing to alter the visible profile of a cylinder as well as the image of the user's touching hand in order to induce the haptic illusion of touching diverse object contours. A related approach was explored by Kohli in virtual reality (VR) environments [18]. Instead of processing video, Kohli tracked the user's finger when touching a real object and mapped its movement to a virtual trajectory, effectively creating the illusion of browsing a virtual object with a different shape. The previous approaches require altering the visual channel by using augmented or virtual reality. We instead focus on altering the display features and how they modify the user's haptic perception while exploring it. As Voisin et al. [34] observed, the exploratory procedures used when discriminating angular shapes usually involve static and dynamic position-related signals from both tactile and kinesthetic inputs. We built upon this observation to explore the use of combined perceptual modalities—visual,

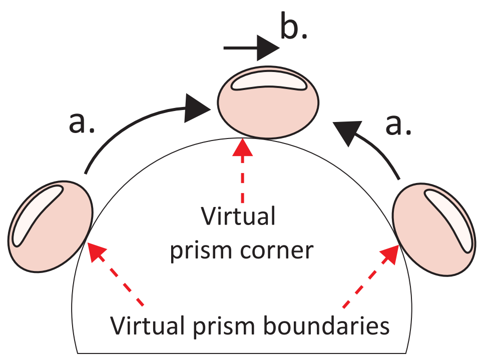

Figure 3. Exploratory procedure used during the experiment for the cylindrical display: a. Vibrotactile feedback is applied when the participant's finger is dragged within the boundaries of the rectangular prism. Feedback amplitude increases linearly as the finger is dragged towards the corner from either side. b. A strong pulse is produced when the finger crosses the corner line, and feedback is stopped.

kinesthetic and tactile—to induce the haptic perception of angular shape on a cylindrical display.

EXPERIMENTAL STUDY

We were interested in studying the interplay of shape, image and haptic feedback. As indicated by Ernst et al. [9], humans combine the visual and haptic feedback channels integrally to assess the properties of objects. Therefore, it was critical to have an actual cylindrical display device as opposed to a simulated 3D-modeled graphic display [28].

Apparatus

We used two display devices, one flat and one cylindrical (see Figure 2). The flat device was an off-the-shelf Android smartphone with a 6.0" (135 mm x 77 mm) FOLED display (with 1280 x 720 pixels of resolution). In order to build the cylindrical device, we wrapped an identical display around a custom 3D printed cylindrical structure with a 28 mm radius (Figure 1). The display was connected to an Android board enclosed inside the cylinder, which was powered via USB. The device was mounted on a tilted platform to keep its lateral surface facing the user.

Touch Detection

In contrast to the flat device, the cylindrical device did not have a working touch sensor. To solve this, we added a transparent layer made of a polyethylene terephthalate (PET) substrate coated with indium tin oxide (ITO), a conductive material. We connected this layer to an Arduino microcontroller, effectively using it as an on/off capacitive touch sensor [2]. In order to detect the touch position, we used a Leap Motion [26] sensor, a device capable of detecting the position of the user's individual fingertips. Both the Arduino and the Leap Motion were connected to an iMac running Mac OS X. The experiment was controlled on this computer by a Max/MSP [25] patch.

Image

The displays had identical technical specifications and both were fully functional and capable of displaying full-color graphics. To minimize visual artifacts due to hard reflections on screen surfaces, the room light was slightly dimmed during the experiment.

Vibrotactile Feedback

We attached a vibrotactile haptic actuator (a Haptuator Mark II [7]) to each device. We drove this actuator by amplifying the audio output from the experiment computer. The actuator transforms the audio signal into vibration of the surface of the displays. We designed a signal to emulate the friction produced when touching the corner of a rectangular prism with a finger. This audio signal was created in Max/MSP and consisted of a train of impulses (one impulse every 5ms) band-pass filtered between 100Hz and 400Hz. It was summed with a white noise signal low-pass filtered at 2KHz at a signal-to-noise ratio of about 17 dB. The signal was active when the user dragged a finger horizontally within the boundaries of the prism image, and its amplitude increased linearly as the finger approached the corner from any of the sides (Figure 3a). When the corner line was crossed, a strong single impulse was generated, and the vibrations were stopped immediately (Figure 3b). Note that the vibration signals are not meant to be heard. Hence, to avoid distractions due to any audible artifacts produced by the actuator, participants were asked to wear a headset that played white noise. A pilot test suggested that low-pass filtering of this white noise signal at 1.2KHz provided sufficient masking of artifacts while not being distracting to participants.

Experimental Design

We invited 19 subjects (11 female) with ages ranging from 19 to 31 years (mean = 22.95, SD = 3.49), to participate in a lab-based experiment. We used a factorial, within-subjects experimental design with three factors:

Shape: The shape of the device, as described in the Apparatus section, with 2 levels: *Cylindrical* or *Flat*.

Image: Two levels: *Rectangular Prism* or *No Image*. In the first condition, a 2D image of a 3D rectangular prism was presented on the display (see Figure 2), with one of its corners facing the participant. The size of the prism as displayed on the screens was 50 mm x 50 mm. For the cylindrical version, we slightly adjusted the profile of the image to compensate for the distortion due to viewing the cylinder surface from the perspective of the participant. In the second condition, only a black background was displayed.

Tactile Feedback: Two levels: In the *Tactile Feedback* condition the vibrotactile stimulus was presented, while in the *No Tactile Feedback* condition, the vibrotactile stimulus was absent.

The combination of these factors yielded 8 conditions that were presented in random order to each participant. We considered that, given the amount of conditions and participants, a randomized presentation best provided balanced presentation without introducing confounding

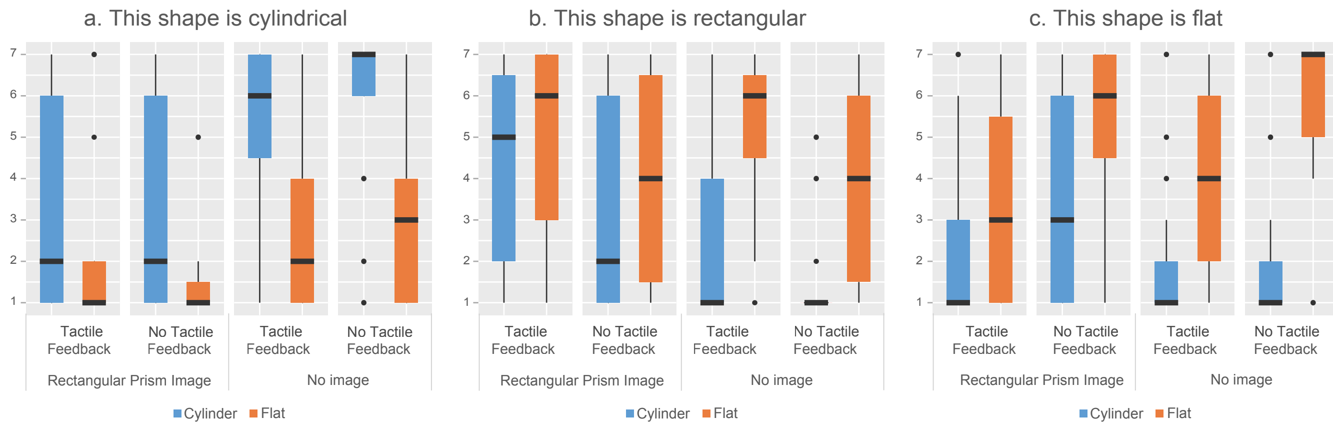

Figure 4. Boxplots for scores of participants' responses (7-point Likert scale, N = 19).

factors. For each condition, we asked participants to touch the surface of the display devices with the tip of the index finger of their dominant hand while dragging horizontally. Participants were allowed to browse the surface for as long as they wanted and as many times as they wanted for each condition. After finishing browsing, we asked them to state their level of agreement with three statements, using a 7-point Likert scale ("Strongly Disagree" to "Strongly Agree"). The statements were "*This shape is cylindrical*", "*This shape is rectangular*", "*This shape is flat*". These three statements were presented in random order per condition.

RESULTS

Boxplots representing the scores of participants' answers to the three questions can be found in Figure 4. Given the scarcity of non-parametric methods for analyzing results of factorial designs, we ran an ANOVA test on the Aligned Rank Transform [35] to find significant effects and interactions. We ran separate tests for every question. We found several significant main effects as well as interaction effects for each question. Besides those explained next, no other significant interactions were found:

The Shape is Cylindrical

The analysis indicated a significant main effect for *Shape* ($F(1,18) = 45.69$, $p < 0.01$), and for *Image* ($F(1,18) = 23.70$, $p < 0.01$). We also found a significant interaction effect between *Shape* and *Image* ($F(1,18) = 9.59$, $p < 0.01$).

The Shape is Rectangular

For this question, we observed a significant main effect for both *Shape* ($F(1,18) = 22.49$, $p < 0.01$) and *Tactile Feedback* ($F(1,18) = 15.72$, $p < 0.01$). There was again a significant interaction effect between *Shape* and *Image* ($F(1,18) = 12.47$, $p < 0.01$).

The Shape is Flat

Finally, for this question, analysis indicated the presence of significant main effects for *Shape* ($F(1,18) = 49.92$, $p < 0.01$) and for *Tactile Feedback* ($F(1,18) = 7.31$, $p < 0.01$). There was also a significant interaction effect between *Shape* and *Tactile Feedback* ($F(1,18) = 8.19$, $p = 0.01$) and between *Shape* and *Image* ($F(1,18) = 10.261$, $p < 0.01$).

DISCUSSION

Unsurprisingly, the actual *Shape* of the display was an influencing factor, as evidenced by its significant main effect across the three questions. However, both presenting an *Image* and *Tactile Feedback* also had significant effects on shape ratings. When a *Rectangular Prism* was displayed, shape was perceived as less cylindrical (Figure 4a).

In the case of a cylindrical device, the presence of the *Rectangular Prism* image made it feel significantly more rectangular (Figure 4b). Similarly, vibrotactile feedback made both devices feel significantly more rectangular (Figure 4b). The cylindrical display appeared initially at a disadvantage here, presumably because the flat display does exhibit one characteristic of a rectangular shape: a flat side. However, when a *Rectangular Prism* image and *Tactile Feedback* were added to the cylindrical display, such differences appeared no longer significant (Figure 4b). Perhaps our most salient finding, then, is this interaction effect between display shape and image presence affecting the salience of tactile feedback only on the cylindrical display. We believe the cylindrical shape of the display made tactile feedback significantly more effective when a rectangular prism image was shown. This might be explained by kinesthetic feedback reinforcing the feeling of touching a volume. When no image was present the effect of the tactile feedback on perceived rectangularity only persisted for the flat device.

Similarly, the presence of tactile feedback significantly reduced the perception of the devices being flat (Figure 4c). This was even the case for the flat device, independently of what was displayed. For the cylindrical device, however, the effect was again only significant when an image was present. Results suggest there may be a synergistic interaction between perceptual modalities when exploring the shape of virtual objects on shaped displays that are augmented with vibrotactile friction stimuli.

Applications

Given that this type of device has been very difficult to build in the past, we believe the design space shows great potential for the exploration of rich haptic experiences. Results point to novel interaction techniques that only a cylindrical display could provide. Applications exist in the domain of gaming, where cylindrical display devices could be used as controllers that display virtual objects in 360 degrees. Priyadarshana et al. [30] shows how a 340 degree cylindrical display can make virtual objects appear three dimensional, particularly when motion parallax is added. Vibrotactile simulations may provide an additional sense of dimensionality and realness to virtual objects displayed on cylindrical displays by simulating presence of a surface contour. This could be useful, for example, when physically animating 3D characters on a cylindrical display by 3D presses "into" the display [16].

Limitations

One limitation to our study is the potential effect of hand holding on the perception of vibrotactile shapes presented on the display. Perception of the virtual shape may not be as salient when the shape sensed by the hand holding the device contradicts that of the fingertip exploring the device [23]. We see a formal investigation of this matter as a potential future direction.

CONCLUSIONS

In this paper, we reported on a study investigating a haptic illusion for altering the perception of 3D shapes displayed on a non-planar screen with vibrotactile friction feedback. In our study, we presented an image of a rectangular prism on a cylindrical and a flat display. Participants were asked to move their index finger horizontally along the surface of the displays towards the edge of the rectangular prism and judge whether they were experiencing a flat, cylindrical or rectangular shape. A vibrotactile stimulus simulating increasing friction towards the visible edge of the rectangular prism was presented in one condition, with a sudden drop-off when this edge was crossed by the finger. Results suggest that all factors (presentation of a rectangular prism; shape of display; and vibrotactile feedback) significantly affected participant ratings, as did interactions between these factors. Presenting an image of a rectangular prism, and applying vibrotactile friction, particularly on a cylindrical display, significantly increased participant ratings stating that they were experiencing a physical rectangular shape. It is worth mentioning that our results apply only to the described experimental design, which involved one-finger touch. Future work should address alternative scenarios, including holding the experimental devices with the non-touching hand. We conclude that the interplay of 3D visual, kinesthetic and vibrotactile shape cues provides fertile grounds for future exploration of shape-changing user experiences.

ACKNOWLEDGEMENTS

We thank Danny Grant of Immersion Inc. for his advice and support. We thank NSERC of Canada and Immersion Inc. for their funding of this work.

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