HaptoBend: Shape-Changing Passive Haptic Feedback in Virtual Reality

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ABSTRACT

We present HaptoBend, a novel shape-changing input device providing passive haptic feedback (PHF) for a wide spectrum of objects in virtual reality (VR). Past research in VR shows that PHF increases presence and improves user task performance. However, providing PHF for multiple objects usually requires complex, immobile systems, or multiple props. HaptoBend addresses this problem by allowing users to bend the device into 2D plane-like shapes and multi-surface 3D shapes. We believe HaptoBend's physical approximations of virtual objects can provide realistic haptic feedback through research demonstrating the dominance of human vision over other senses in VR. To test the effectiveness of HaptoBend in matching 2D planar and 3D multi-surface shapes, we conducted an experiment modeled after gesture elicitation studies with 20 participants. High goodness and ease scores show shape-changing passive haptic devices, like HaptoBend, are an effective approach to generalized haptics. Further analysis supports the use of physical approximations for realistic haptic feedback.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; *Haptic Devices*

KEYWORDS

Virtual Reality; Shape-changing interactions; haptic feedback;

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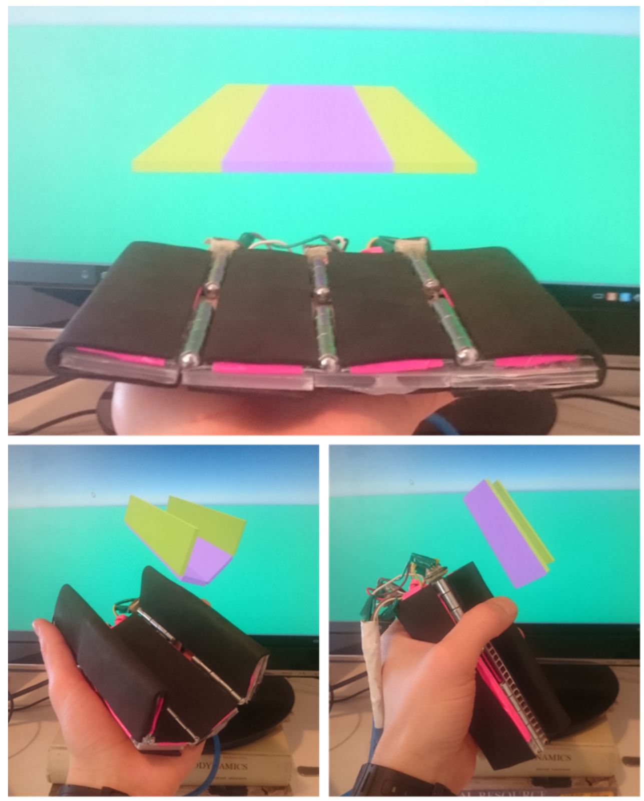

Figure 1. HaptoBend and its real-time digital reconstruction.

1 INTRODUCTION

Haptic feedback in virtual reality (VR) provides a demonstrable improvement to both presence [1, 17, 18] and user performance in virtual environments (VE) [4, 38, 40]. In the absence of haptic feedback, the disparity between visual and physical experiences negatively affects presence [37] during direct contact with a virtual object. Likewise, the absence of tangible interaction removes an important reference and constraints in 3D manipulation tasks. Yet, much of the development in VR focuses on advancements in the visual aspects of VEs, while haptic feedback in VR shows much slower progress [3, 6].

Even though a variety of commercial and research haptic devices exist [10, 28], none have gained the traction of modern head-mounted displays. Past approaches separate VR haptics into two main categories: Passive haptic feedback (PHF) and active haptic feedback (AHF). PHF relies on static physical objects (i.e., props) to provide tactile feedback for virtual objects [3], while AHF displays use an integrated system of powered actuators to provide haptic feedback [46]. Both present problems for supplying haptic feedback to a variety of virtual objects.

PHF requires a separate physical prop to stand in for each virtual object [4, 17]. Accommodating a variety of virtual objects leads to an impractically large number of props, which can be expensive, complex and immobile. AHP systems rely on intrusive, expensive mechanical systems that lack mobility and are inaccessible to many recreational users [7, 31, 35].

HaptoBend (Figure 1) takes an original approach to address these problems through a single hand-held shape-changing device. HaptoBend's four hinged panels allow it to provide PHF for a variety of virtual objects by transitioning between 2D, plane-like shapes, and multi-surface 3D shapes. Through its shape-changing capabilities, HaptoBend avoids the size, complexity, and cost of general purpose haptic systems. While past research shows many bendable, plane-like prototypes [14, 15, 23, 27, 34], none have been applied to VR for general PHF.

Our approach draws on the dominance of human vision over other senses, allowing physical approximations for haptic feedback [3, 12, 22, 36, 45, 46]. Therefore, we believe HaptoBend can allow realistic haptic feedback for 2D and 3D virtual objects by enabling users to approximate the physical attributes of a virtual object, eliminating the need for numerous physical props.

We evaluated HaptoBend's ability to facilitate PHF for a variety of 2D and 3D virtual objects. In an experiment modeled after gesture elicitation studies, participants selected their preferred shape for HaptoBend to map to 2D and 3D virtual objects of three sizes. To the best of our knowledge this marks the first elicitation study for PHF in VR. The results of our work provide the following contributions to VR haptic research:

- The design for a shape-changing PHF device compatible with a range of virtual objects.
- The first elicitation study exploring preferred PHF shapes for virtual objects using a shape-change device.
- Further evidence that physical approximations are sufficient when providing PHF for 2D and 3D virtual objects.

2 RELATED WORK

Past research in VR shows benefits of haptic feedback in both spatial awareness and presence [18]. We look at the two main categories of haptic feedback, PHF and AHF, to identify their benefits and shortcomings. We then expand the scope of passive haptic devices by relating them to shape changing devices with similarities to HaptoBend. Finally, we provide a review of gesture elicitation studies and their use in related contexts.

2.1 Passive Haptics

A long history of research in VR supports the benefits of PHF. Hinckley et al. [16] were some of the first researchers to explore the benefits of PHF in 1994 by assessing the use of a tracked doll head as PHF for 3D brain models.

One direction of PHF maintains the use 3D props as physical proxies. Using physical replicas of spiders for PHF, Carlin et al. [9] and Garcia et al. [13] performed early studies which showed VR as effective in treating arachnophobia. Hoffman et al. [17] was the first to provide empirical evidence to support the benefits of PHF. Such studies continue today, for example the recent work by Besançon et al. [4] showing benefits of 3D props over touch and mouse-based interactions. Jackson et al. [19] demonstrated 3D prop construction using cheap materials such as a rolled tube of paper, making PHF affordable for a small number of virtual objects.

Another common approach is the use of 2D plane-like surfaces for a variety of 2D interactions. One of the earliest examples is seen in the work of Stoakley et al. [38], where a clipboard served as PHF for a worlds in miniature metaphor. Lindeman et al. [26] contributed early findings on the benefits of hand-held devices over fixed devices. Increased selection task performance through this method are also supported by the work of Teather et al. [40] and Joyce & Robson [20].

While 2D and 3D props demonstrate benefits, research also points the drawback of requiring separate physical objects for each virtual object. Most notably these include the volume and complexity of prop switching, a difficult challenge to avoid with a variety of virtual objects.

Taking a similar approach to ours in mitigating these problems, Aguerreche [1] offers the only general VR PHF device that we know of that allows shape-change other than HaptoBend. While their prototype provides only a skeletal representation of virtual objects they found it increased presence, and realism over non-tangible techniques.

2.2 Active Haptics

Some of the earliest work in AHF by Brooks et al. [7] used a giant mechanical arm to supply resistance, similar to the smaller PHANTOM [28] developed in 1994. The latter is still commonly used today for AHF research. Contributions from both to AHF continue to influence current work, much of which explores generalized AHF systems using an actuated exoskeleton. These can vary in size and complexity from wall mounted, full-arm exoskeletons like the EXO-UL3 [31], pulley-based systems like the SPIDAR [35], and smaller, single-hand versions such as the Rutgers Master II [5] and Wolverine [11]. These systems illustrate the potential of AHF for a variety of virtual objects.

The main drawback of AHF is its reliance on limiting individual joints using an apparatus that is either large, complex, intrusive, expensive or a combination of these. Active haptics can also lack the robust physical feedback of solid PHF props, depending on how strong their actuators are. Ultrahaptics [10, 39], which use areas of converging ultrasound to provide AHF, are especially prone to this flaw.

2.3 Visual Dominance in PHF

Recent research has demonstrated the dominance of human vision over other senses, including touch [3, 12, 22, 36, 45, 46], suggesting great promise for generalized haptic systems. Work in this area shows potential for single PHF devices being effective for multiple virtual objects. Simeone et al. [36] found 3D PHF props can still be effective when shape is not an exact match to corresponding virtual objects. Research by Kwon et al. [22] did not find significant differences in comparing PHF size differences for a consistent virtual object. Visually warping a VE can also allow a single PHF device to act as many, seen in the work of Azmandian et al. [3].

Zenner et al. [46] highlighted the importance of weight in PHF with Shifty, a wand with actuating weight distribution. Their study showed weight changes could be emulated through approximations and enhanced through visual animations. Dominjon et al. [12] also looked at weight, and showed increases in the control/display ratio lead to a lighter perception of virtual objects.

2.4 Shape-Changing Devices

While PHF devices are useful in multiple contexts, we are unaware of any single device that supports both 2D and 3D interactions in VR. Shape changing input affords users the ability to change between 2D and 3D states but does not hold a prominent position in current VR research. However, many examples outside of VR show benefits through the addition of tactile feedback.

FlexSense [34] and Hermanis et al. [15] provide two examples of shape-changing devices with potential in VR. Both offer rich sensing to create real-time digital reconstructions of their shape. The use of internal sensors by both devices also means they avoid issues of occlusion found in optical tracking.

PaperFold [14] consists of rigid displays with detachable hinged connections allowing up to four displays to be combined. When participating in 3D interactions with PaperFold, users preferred transitioning from a 2D shape to a 3D triangular prism. In addition, the researchers mention PaperFold strikes a good balance between mobility and shape resolution for a wired device. As a result, our design for HaptoBend took inspiration from this study. However, differences between HaptoBend and PaperFold are still prevalent, not only in the context of their use but in their physical size and approach to bend sensing.

Lindlbauer et al. [27] created a display integrating spatial augmented reality through projection mapping with a shape-changing interface by actuating folds in a piece of paper. Projecting onto the shape-changing paper complimented 3D graphics through depth cues and showed increases in "realism" and immersion during an informal study. Paddle [33] used projection mapping and rigid planes connected by hinges to create a mobile device. The added physical interactions Paddle allows through shape change resulted in faster peeking and more accurate leafing interactions when compared to touch input.

Ninja Track [21] follows the 2D to 3D metaphor by changing from a state with paper-like flexibility found in a 2D plane, to a rigid, rod-like state akin to 3D objects. Applications they explored included gaming through changing from a sword to a whip, and music by creating the sounds of instruments it physically mimics. LineFORM [29] allows a diversity of interactions through actuated shape-change. Consisting of a chain of servo motors, it can approximate a variety of shapes to provide passive and active haptics, and allow input through direct manipulation.

2.5 Gesture Elicitation Studies

Wobbrock et al. [43, 44] provided the initial structure for gesture elicitation studies. In their method participants are shown an action and asked to map a gesture to it. An agreement score is then calculated for each action, showing the level of consensus for the most preferred corresponding gesture. Further work by Vatavu & Wobbrock [41] improved the method for calculating agreement scores by increasing accuracy.

Initially used for measuring consensus in multi-touch gestures, elicitation studies are now commonly used throughout the field of HCI. Lee et al. [25] and PaperPhone [23] show the adoption of gesture elicitation studies for tangible UIs allowing deformation. Gesture elicitation studies have also been applied to the manipulation of digital 3D objects in screen-based 3D UIs [8] and augmented reality [24, 32]. Our study applied gesture elicitation studies to assess shape preferences for PHF enabled by HaptoBend.

3 METHODOLOGY

We performed a user study to test HaptoBend's potential for 2D and 3D PHF. To collect qualitative data on participants' first impressions, we asked them to think aloud while familiarizing themselves with HaptoBend. Next, we guided participants through an exercise based on gesture elicitation to test which PHF shapes users preferred for a variety of virtual objects. Participants rated each preferred HaptoBend shape in terms of goodness and ease to gain insight into the quality of their interactions. Participants then shared their final thoughts on the pros and cons of the device.

3.1 Participants

We recruited 20 participants, aged 21 to 38 years (μ = 27.8 years). Twelve participants were male, 7 were female and 1 answered other. The majority used VR, played video games and used 3D modelling software at least once a month. Four used VR daily, while 3 had never experienced VR before.

3.2 HaptoBend Prototype and Apparatus

HaptoBend integrates four 1.5" x 5" rigid sections with hinged connections. Together, the panels create a bendable plane measuring 6" x 5" when lying flat and weighing 358.8 grams. Our approach to the construction draws from past flexible plane devices [14, 15, 34]. While earlier devices are similar, none combine the same construction and sensing methods to create a digital reconstruction of the device in VR.

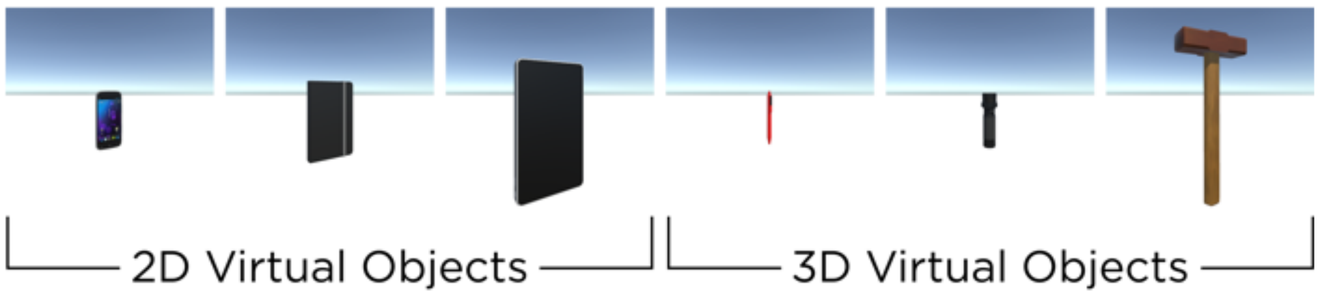

Figure 2. Virtual objects used in shape elicitation. Left to right: smartphone, notebook, tablet, pen, flashlight and sledge hammer.

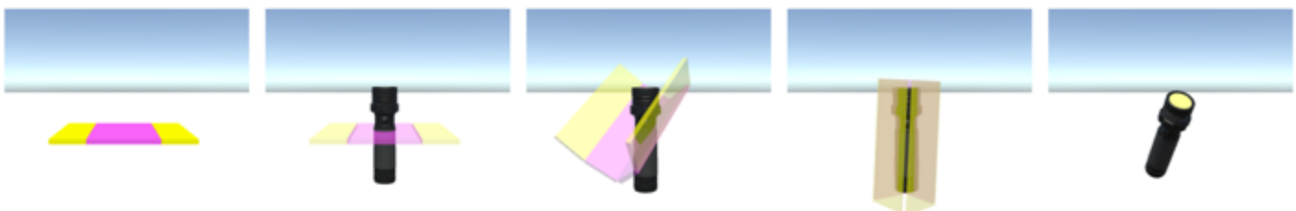

Figure 3. Example of HaptoBend mapping process to a virtual object: the virtual object appears (left); the participant determines their preferred shape (middle images), before notifying the experimenter that the shape is ready; the virtual model of HaptoBend disappears and the participant controls the rotation of the virtual object with the prototype (right).

The HaptoBend prototype is seen in Figure 1. Twist potentiometers located at each hinge axis sense the bend angle of each panel. An Adafruit BNO055 IMU senses yaw, roll and pitch of the entire device. The sensors all provided input to an Arduino Uno feeding serial data to a PC running Windows 10 (64 bit) with a 3.2GHz CPU, 8GB of RAM, and a NVidia GeForce GTX1060 3GB GPU. An Oculus Rift *CV1* head-mounted display presented the VE to users.

We integrated all the hardware together in Unity 5.5. A C# script utilized the SerialPort class to capture incoming serial data from the Arduino, while the *CV1* integrated through the Oculus SDK for Unity. We used custom C# scripts to transform information from the sensors into a real-time digital representation of HaptoBend in the VE.

The VE depicted a simple scene consisting of a flat plane, a horizon, a model of HaptoBend (Figure 1), and, during elicitation, a virtual object (Figure 2). The 3D model of HaptoBend reflected the bend angle of each panel and the device's overall rotation in real time (Figure 3). We simultaneously displayed the "target" virtual object and HaptoBend's 3D model when we asked participants to perform interactions between the two. The six virtual objects we used can be seen in Figure 2. We selected the virtual objects to provide three objects commonly used for 2D interactions, and three objects commonly used for 3D interactions, across three size categories: one roughly the same size as HaptoBend (called "medium"), one smaller, and one larger. The 2D models were a smartphone, a notebook and a large tablet, while 3D objects consisted of a pen, a flashlight and a sledge hammer. We used royalty-free 3D models for all virtual objects.

3.3 Procedure

After participants completed a consent form and demographic questionnaire, they received a detailed description of HaptoBend as a flat plane with the ability to bend at its panel connections to create 3D shapes. The experimenter assisted each participant with fitting the *CV1* correctly and ensured proper use of all devices during the study.

3.3.1 Think Aloud. The first section of the study follows the think aloud assessment presented by Ahmaniemi et al. [2]. The experimenter asked each participant to familiarize themselves with HaptoBend by contorting it into different shapes and brainstorming applications for the device in VR. The researcher gathered general qualitative data from this exercise.

3.3.2 Shape Elicitation. The elicitation phase draws on the work of Wobbrock et al. [43, 44] to assess if HaptoBend's physical approximations of virtual objects create satisfactory PHF. Research by Gomes et al. [14] contributed to examine if participants prefer using HaptoBend as a 2D shape for 2D virtual objects and 3D shapes for 3D virtual objects.

Upon starting the shape elicitation phase, target object models appeared one at a time co-located with the 3D model of HaptoBend (Figure 3). Following our instructions, participants held HaptoBend in the shape and orientation perceived most preferable for controlling the virtual object. Participants could choose any shape they wanted subject to the physical limitations of HaptoBend. They performed this task with the intent of using the target object as they would in the real world. Upon completing the task, participants notified the experimenter who pressed a key, which caused the HaptoBend model to disappear and applied its rotation the virtual object. Figure 3 illustrates an example of the mapping process.

Similar to Wobbrock et al. [44], after selecting each mapping, participants verbally rated it in terms of goodness and ease on a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree). For goodness participants rated the statement, "The shape I picked is a good match for its intended purpose" while participants rated, "The shape I chose was easy to perform" for ease. After completing both the think aloud and shape elicitation phases, participants completed a post-questionnaire, which asked them to record what they liked and disliked about HaptoBend.

3.4 Design

The shape elicitation phase employed a 2 × 3 within-subjects design with the following independent variables and levels:

- *Object type*: 2D flat objects, 3D multi-surface objects
- *Object size*: small, medium, large

yielding the six different virtual object combinations (Figure 2). Each participant mapped HaptoBend to each of the 6 virtual objects once. Across all 20 participants, this resulted in 120 trials. To counterbalance fatigue and training effects, we randomized the order of the virtual objects for each participant.

We recorded three dependent variables during the elicitation phase: shape (the shape users deformed HaptoBend into), goodness (how well the chosen shape allows control of the object), and ease (ease of creating the chosen shape with HaptoBend). We also calculated agreement scores using the process outlined by Vatavu & Wobbrock [41], as described in Section 4.3.

4. RESULTS

We first present participants' impressions of HaptoBend gathered from the think aloud phase and post-questionnaire. Next, we report shape elicitation results.

4.1 User Impressions

Participants described HaptoBend as enjoyable and easy to use. When asked to think of possible applications for HaptoBend, most were already thinking of objects it could physically represent in VR, the most popular being a book. Other popular applications included a video game controller and creating primitive shapes in 3D modeling and CAD software.

Upon completing the experiment, participants shared their overall thoughts on HaptoBend. Positive feedback included 10 participants praising HaptoBend's responsiveness, followed by 9 enjoying the foam texture, 8 valuing its ability to bend, and 8 appreciating the digital model of the device. Six participants also saw its diversity of application as a plus. In terms of negative feedback, 6 participants noted the limits of including only three hinged areas, 5 expressed dissatisfaction with the inability to fold the device completely flat, and 5 saw the size difference between some virtual models and the device as a negative.

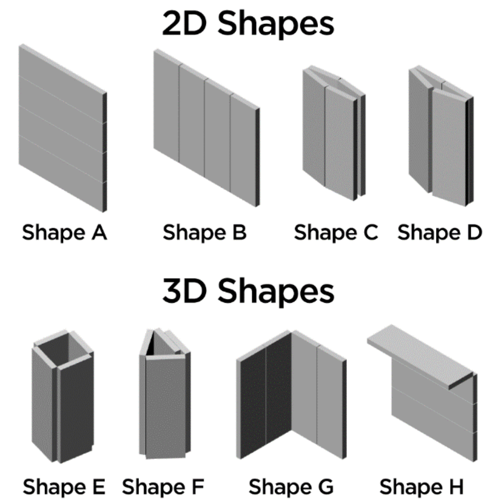

Figure 4. Shapes produced by participants during the elicitation section.

4.2 Shapes

We allowed participants to reuse shapes for different virtual objects, as in Wobbrock et al. [44], which led to a total of 8 original shapes, illustrated in Figure 4. We classified four as 2D shapes and four as 3D shapes. Shapes received the designation "2D" if the intent of the shape was to create a single flat plane, while we classified shapes that utilized multiple, intersecting planes as "3D".

Figure 5 shows shape-use frequency for each virtual object. Participants used Shape E the most for 3D shapes and overall with 28 uses. Totals for the rest of the 3D shapes amount to 24 for F, 1 for G, and 1 for H. Shape A showed the highest use of 2D objects with 21 uses followed by shapes B and C with 19, and 7 for D.

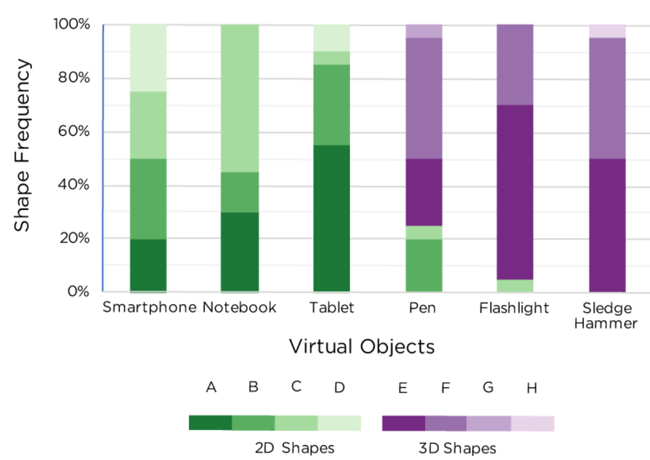

Figure 5. Frequency of use for each shape as mapped to each object type and size.

As expected, frequency of use changed to match the virtual object encountered. The most common shapes for the 2D virtual objects were Shape B for the smartphone, Shape C for the notebook and Shape A for the tablet. The most common shapes for the 3D virtual objects were Shape F for the pen, Shape E for the flashlight, and Shape E for the sledge hammer.

4.3 Agreement Scores

Agreement scores represent participant consensus in the shapes mapped to each virtual object. An agreement score of 1 means all participants chose the same shape for a given virtual object, as the score lowers it indicates larger variety in the shapes chosen for a given virtual object. Most past elicitation studies relied on the method proposed by Wobbrock et al. [43, 44]. We employ an updated equation outlined by Vatavu & Wobbrock [41] which, unlike the previous approach, puts scores on a true 0-to-1 scale. As a result, agreement scores are lower, however, they are more accurate, allow calculation of coagreement scores, and enable statistical significance tests. Per Vatavu & Wobbrock [41], we can calculate agreement score (AR) with equation (1).

$$AR(r) = \frac{|P|}{|P|-1} \sum_{P_i \subseteq P} \left(\frac{|P_i|}{|P|}\right)^2 - \frac{1}{|P|-1} \quad \textbf{(1)}$$

For virtual object r, P is the total number of shapes participants used in the elicitation exercise and Pi is a set of identical shapes within P. Equation (2) shows an example of this equation in use to calculate the agreement score for the virtual sledge hammer, where participants selected three different shapes.

$$AR(hammer) = \frac{|20|}{|20|-1}\left(\left(\frac{10}{20}\right)^2 + \left(\frac{9}{20}\right)^2 + \left(\frac{1}{20}\right)^2\right) - \frac{1}{|20|-1} = 0.426 \quad \textbf{(2)}$$

We calculated agreement scores for each virtual object as seen in Figure 6. Scores range from 0.216 to 0.489, with the smartphone receiving the lowest score, and the highest achieved by the flashlight.

To compare agreement scores we used Cochran's Q test as outlined by Vatavu & Wobbrock [41], which yielded 7 significantly different pairs of conditions. The smartphone's agreement score was significantly lower than the notebook ($V_{rd(1, N=40)} = 13.47$, $p < .001$), the tablet ($V_{rd(1, N=40)} = 8.12$, $p < .01$), the flashlight ($V_{rd(1, N=40)} = 31.44$, $p < .001$), and the sledge hammer ($V_{rd(1, N=40)} = 18.61$, $p < .001$) virtual objects. The agreement score for the pen was significantly lower than the flashlight ($V_{rd(1, N=40)} = 21.83$, $p < .001$) and the sledge hammer ($V_{rd(1, N=40)} = 10.92$, $p < .001$). Finally, the flashlight had a significantly higher agreement score than the tablet ($V_{rd(1, N=40)} = 7.84$, $p < .01$).

In addition, we calculated agreement scores for the broader categories of 2D shapes and 3D shapes for each virtual object. This facilitated an assessment of whether participants prefer 2D or 3D PHF shapes when mapping to virtual objects intended for 2D vs. 3D interactions. All objects received an agreement score of 1 except for the pen (score of 0.605) and the flashlight (score of 0.900). This indicates that five objects received a perfect (or almost perfect) match between the dimension of the shape to that of the virtual object. These results show high consensus for mapping 2D virtual interactions to 2D shapes and 3D virtual interactions to 3D shapes.

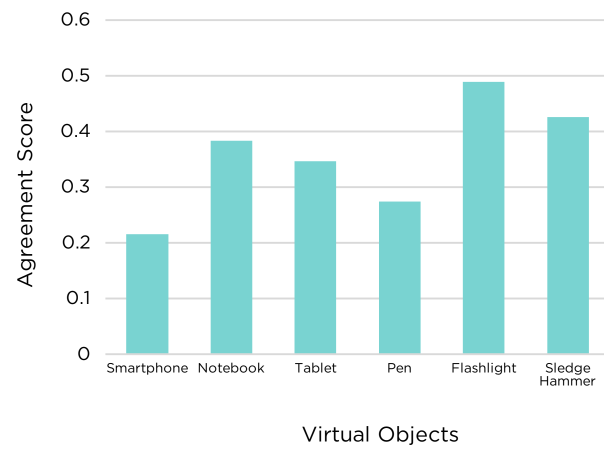

Figure 6. Agreement scores for each virtual object.

4.4 Goodness and Ease Ratings

Participants rated the shapes produced for each virtual object in terms of **goodness**, i.e., quality of the mapping. Overall ratings for all the shapes were positive, except for Shape G. Goodness scores are seen in Figure 7. These results show positive ratings for all objects, with the flashlight and sledge hammer receiving exclusively positive ratings.

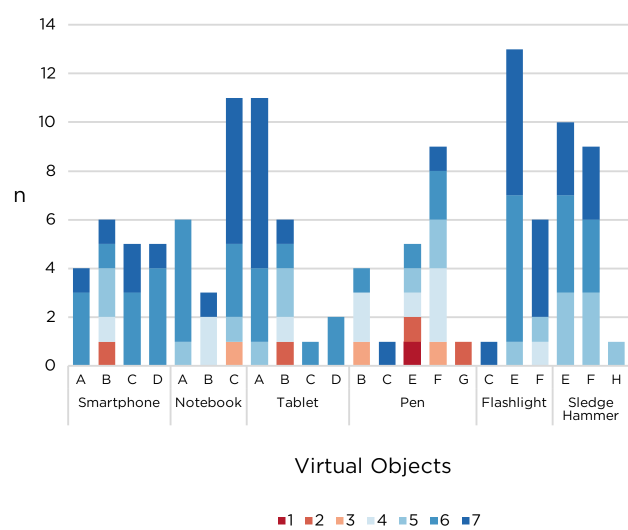

Figure 7. Goodness rating summed for each shape within each virtual object presented to participants.

To compare overall goodness ratings between virtual objects we used the Mann-Whitney U test. The goodness ratings for the pen were significantly lower than all the other objects: smartphone ($U = 94.0$, $p < .05$) notebook ($U = 94.0$, $p < .05$), tablet ($U = 88.5$, $p < .005$), flashlight ($U = 61.0$, $p < .001$), and sledge hammer ($U = 84.5$, $p < .001$).

Ease ratings allow an assessment of HaptoBend's ability to deform into a participant's desired shape. We also summed ease rating results for each shape-object mapping (Figure 8). The only virtual objects showing a negative ease rating are Shape G mapped to the pen and Shape A mapped to the tablet.

5 DISCUSSION

Our study resulted in participants generally agreeing on their preferred PHF shape for each virtual object, feeling positive about their choices' goodness and encountering little to no trouble with each shape's ease of use. Participant comments also reinforced our quantitative results. These findings support HaptoBend as a simple, mobile and more accessible alternative to large, complex and costly general purpose haptic systems.

5.1 2D vs 3D Shape Mapping

One of our objectives with this study was to gain insight into whether users show a preference in their mapping of PHF shapes to virtual objects. We predicted that they would map shapes with objects of the same dimension: 2D PHF shape to 2D virtual objects and 3D PHF shapes to 3D virtual objects. Our results across all measures strongly suggest that this is indeed the case. The frequency of shapes used for each virtual model and the agreement scores comparing 2D and 3D shapes are good indicators of support.

Participants mapped a strong majority of the virtual objects to shapes of the same dimension. The two exceptions to this were the pen and the flashlight, with 25% and 5% of participants mapping them to 2D shapes respectively (Figure 5). The resulting goodness and ease ratings for the pen are the lowest of all the objects showing the use of 2D shapes for 3D objects may have a negative effect. Observing this type of behavior points to the importance of further development in shape-changing PHF devices, like HaptoBend, to facilitate 2D and 3D interactions in VR.

5.2 Approximating Shapes

We used a relatively simple and inexpensive design for HaptoBend, based on the work of Simeone et al. [36] who showed physical approximations of virtual objects produce satisfactory PHF. The results from our elicitation study support Simeone's findings [36]. Participants consistently rated approximate shapes made with HaptoBend as good PHF for more detailed virtual objects. These results also align with findings from Aguerreche et al. [1], which supports the use of physical approximations for PHF in VR. One participant summed the effects of shape approximation best when mapping to the pen stating: "Even the lack of roundness doesn't really matter. What matters more is that it feels like I'm holding some sort of elongated barrel shape in my hand." The quote is especially significant when one considers that the pen yielded our weakest overall results.

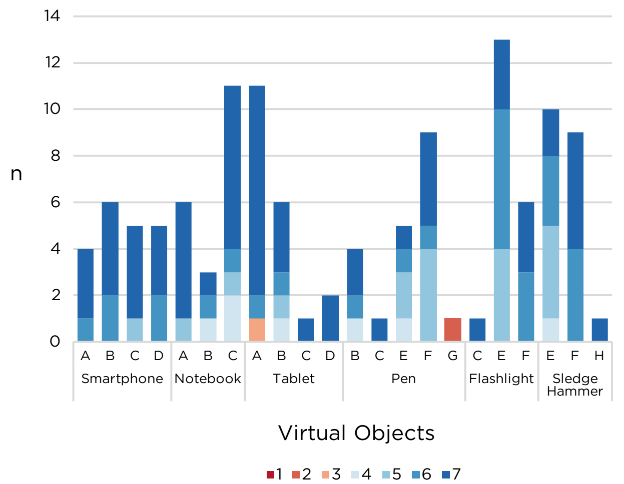

Figure 8. Ease rating responses for ease summed over the entire elicitation phase for each shape.

The flashlight performed especially well with the highest agreement score and the high goodness ratings. Seven participants even mentioned no noticeable difference between HaptoBend's angular shapes and the cylindrical flashlight. One went as far as saying, "I don't think you could get any closer to the shape (of the virtual object)" and another stated, "this feels like a flashlight." The sledge hammer, and notebook received less pronounced but similar results, with agreement scores and goodness ratings that were not significantly different from the flashlight.

Some of our virtual objects illustrate possible limitations to how strongly vision dominates touch, as reported by Simeone et al. [36]. The tablet, smartphone and pen all received significantly lower agreement scores than the flashlight. Even with less impressive results these virtual objects still received high goodness ratings and encouraging comments from participants. Enabling shapes that more closely matching the size and shape of these virtual objects might lead to improvements here.

We note that the smartphone had the lowest agreement score. HaptoBend's physical constraints appear to be an influence here as they limit the device's hinges from rotating a full 180°. As a result, the Shapes C and D, the closest in size to the smartphone, could not fold completely flat. Nine participants mentioned this physical constraint as a problem. Four commented they would have chosen shapes C or D, but instead chose larger Shapes A or B to achieve a completely flat shape. Since the functionality of a smartphone is dependent on using a flat touchscreen, participants had to choose between a shape similar in size, or a shape perceived to more closely fit the function of this virtual object.

Functionality factored into the participants' opinions of the tablet as well. Using shape A, the closest in shape to a tablet, would position HaptoBend's wire connections in a conflicting location for conventional tablet grip positions [42]. Size may also have been a factor as all shapes enabled by HaptoBend were smaller than the tablet. Of all the virtual objects, size impacted the pen most. Eleven participants described HaptoBend as too large to map well to it, which yielded significantly lower goodness ratings compared to all other virtual objects.

5.3 Approximating Weight

While HaptoBend's design allowed changes in shape and size, it does not support changes in weight. As described earlier, Zenner et al. [46] showed the importance of PHF objects approximating a virtual object's expected weight. Our results suggest that HaptoBend is still able to provide PHF for a variety of virtual objects, even without dynamic weight distribution like Zenner et al.'s Shifty [46]. Earlier work by Zenner [45] provides insight into these observations by describing some level of tolerance to weight differences for PHF objects. While we observed some level of disparity, HaptoBend does not differ drastically from the real-world weights of any 2D virtual objects we used. Participants also seemed to tolerate these weight differences well as they rarely mentioned them during the elicitation study.

The range of 3D objects had a larger weight disparity with HaptoBend than the 2D objects. The weight difference with the pen and sledge hammer are particularly pronounced. In general participants felt the weights of HaptoBend and the flashlight were similar, leading to mostly positive comments. The sledge hammer would be far heavier than HaptoBend, however, participants had mixed opinions on this: 2 mentioned weight positively, and 2 mentioned weight negatively. The pen was the only virtual object where participants noticed a pronounced difference in weight. Six participants mentioned HaptoBend was too heavy for this virtual object, contributing its lower goodness ratings.

5.4 Future Improvements

The high goodness and ease scores achieved by HaptoBend point to a high potential for shape-changing devices to provide PHF in virtual environments. Overall, mimicking a virtual object's shape appeared effective in emulating users' expected haptic feedback. These results align with past work from Ninja Track [21] and Aguerreche et al. [1] who took similar approaches by emulating the shape of different real-world objects for digital interactions. Future work should test these findings further with virtual objects that have a larger variety in size and shape. A greater variety of virtual objects would allow richer insight into the ability of HaptoBend produce realistic PHF through approximations of shapes, weight and other physical properties.

Poor performance in agreement for the small virtual objects point to a need for higher resolution shapes by dividing HaptoBend into more panels, or replacing them with a flexible material. Higher resolution would especially improve PHF for smaller and more intricate objects. Another important factor for resolution is hinges that allow 180°, or even 360° rotation, for fully flat bends. In combination, these two improvements would alleviate much of the negative shape feedback HaptoBend received.

Six participants recommended adding a feature that locks HaptoBend's panels to prevent the devices from changing shape once it is mapped. A locking feature would also increase functionality by creating physical consistency for interactions.

At points in the study where participants used HaptoBend to control virtual objects, they were eager to use those objects for their expected functions. However, we note that to support such functions, we would have to add additional sensors. For example, capacitive touch sensors would enable (simulated) touch screen interactions. Adding a 3D position tracker would also facilitate richer spatial interaction. Applying flexibility to normally ridged objects to increase interactions through bend-gestures also gained support by the suggestion of 6 participants.

Functionality also seemed to suffer from the wires connecting HaptoBend's sensors to the computer. A future version of the device could use wireless data transmission (e.g., via Bluetooth) to eliminate this problem, and may yield a better experience. These modifications could lead to mobile version of HaptoBend with the potential for augmented reality applications.

6 CONCLUSION

Developments in VR have created impressive VEs with the ability to bring users original experiences through high-quality graphics. Unfortunately, users experience breaks in presence when haptic feedback fails to align with physical expectations [37]. Current solutions for generalized haptic systems either require a large number of props for PHF [4, 17] or complex mechanical systems for AHF [7, 31, 35]. HaptoBend addresses these shortcomings by providing diverse PHF using shape-change. We believe visual dominance of humans' senses contributes to HaptoBend's effectives for a wide range of virtual objects by allowing physical approximations to result realist PHF.

We performed an elicitation user study to assess our approach to PHF. The elicitation study's results show strong support for HaptoBend's ability to create realistic PHF for a variety of 2D and 3D virtual object representing different sizes. Our findings also build evidence for HaptoBend as a legitimate solution to current issues with traditional PHF and AHF, through its use of physical approximations. The positive performance of HaptoBend points to a bright future for shape-changing PHF devices in VR, with many areas open for further research.

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REFERENCES

[1] Aguerreche, L., Duval, T. and Lécuyer, A. 2010. Reconfigurable tangible devices for 3D virtual object manipulation by single or multiple users. *Proceedings of the ACM Symposium on Virtual Reality Software and Technology* (2010), 227–230.

[2] Ahmaniemi, T.T., Kildal, J. and Haveri, M. 2014. What is a device bend gesture really good for? *Proceedings of the ACM Conference on Human Factors in Computing Systems, CHI '14* (New York, NY, USA, 2014), 3503–3512.

[3] Azmandian, M., Hancock, M., Benko, H., Ofek, E. and Wilson, A.D. 2016.

Haptic retargeting: dynamic repurposing of passive haptics for enhanced virtual reality experiences. *Proceedings of the ACM Conference on Human Factors in Computing Systems. CHI '16* (2016), 1968–1979.

[4] Besançon, L., Issartel, P., Ammi, M. and Isenberg, T. 2017. Mouse, tactile, and tangible input for 3D manipulation. *Proceedings of the ACM Conference on Human Factors in Computing Systems, CHI '17* (2017), 4727–4740.

[5] Bouzit, M., Burdea, G., Popescu, G. and Boian, R. 2002. The Rutgers Master II-new design force-feedback glove. *IEEE/ASME Transactions on mechatronics*. 7, 2 (2002), 256–263.

[6] Brooks, F.P. 1999. What's real about virtual reality? *IEEE Computer graphics and applications*. 19, 6 (1999), 16–27.

[7] Brooks Jr, F.P., Ouh-Young, M., Batter, J.J. and Jerome Kilpatrick, P. 1990. Project GROPEHaptic displays for scientific visualization. *ACM SIGGraph computer graphics* (1990), 177–185.

[8] Buchanan, S., Floyd, B., Holderness, W. and LaViola, J.J. 2013. Towards user-defined multi-touch gestures for 3D objects. *Proceedings of the ACM International Conference on Interactive tabletops and surfaces* (2013), 231–240.

[9] Carlin, A.S., Hoffman, H.G. and Weghorst, S. 1997. Virtual reality and tactile augmentation in the treatment of spider phobia: a case report. *Behaviour research and therapy*. 35, 2 (1997), 153–158.

[10] Carter, T., Seah, S.A., Long, B., Drinkwater, B. and Subramanian, S. 2013. UltraHaptics: Multi-point mid-air haptic feedback for touch surfaces. *Proceedings of the ACM symposium on User interface software and technology, UIST '13* (2013), 505–514.

[11] Choi, I., Hawkes, E.W., Christensen, D.L., Ploch, C.J. and Follmer, S. 2016. Wolverine: A wearable haptic interface for grasping in virtual reality. *IEEE/RSJ International Conference on Intelligent Robots and Systems* (2016), 986–993.

[12] Dominjon, L., Lécuyer, A., Burkhardt, J.-M., Richard, P. and Richir, S. 2005. Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments. *Proceedings of IEEE Virtual Reality* (2005), 19–25.

[13] Garcia-Palacios, A., Hoffman, H., Carlin, A., Furness, T.A. u and Botella, C. 2002. Virtual reality in the treatment of spider phobia: a controlled study. *Behaviour research and therapy*. 40, 9 (2002), 983–993.

[14] Gomes, A. and Vertegaal, R. 2015. PaperFold: evaluating shape changes for viewport transformations in foldable thin-film display devices. *Proceedings of the International Conference on Tangible, Embedded, and Embodied Interaction, TEI '15* (2015), 153–160.

[15] Hermanis, A., Cacurs, R. and Greitans, M. 2016. Acceleration and magnetic sensor network for shape sensing. *IEEE Sensors Journal*. 16, 5 (2016), 1271–1280.

[16] Hinckley, K., Pausch, R., Goble, J.C. and Kassell, N.F. 1994. Passive real-world interface props for neurosurgical visualization. *Proceedings of the ACM Conference on Human Factors in Computing Systems, CHI '94* (1994), 452–458.

[17] Hoffman, H.G. 1998. Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments. *Proceedings of IEEE VRAIS* (1998), 59–63.

[18] Insko, B.E. 2001. *Passive haptics significantly enhances virtual environments*. University of North Carolina at Chapel Hill.

[19] Jackson, B., Lau, T.Y., Schroeder, D., Toussaint, K.C. and Keefe, D.F. 2013. A lightweight tangible 3D interface for interactive visualization of thin fiber structures. *IEEE transactions on visualization and computer graphics*. 19, 12 (2013), 2802–2809.

[20] Joyce, R.D. and Robinson, S. 2017. Passive haptics to enhance virtual reality simulations. *AIAA Modeling and Simulation Technologies Conference* (2017), 1313.

[21] Katsumoto, Y., Tokuhisa, S. and Inakage, M. 2013. Ninja track: Design of electronic toy variable in shape and flexibility. *Proceedings of the International Conference on Tangible, Embedded and Embodied Interaction, TEI '13* (New York, NY, USA, 2013), 17–24.

[22] Kwon, E., Kim, G.J. and Lee, S. 2009. Effects of sizes and shapes of props in tangible augmented reality. *Proceedings of IEEE ISMAR* (2009), 201–202.

[23] Lahey, B., Girouard, A., Burleson, W. and Vertegaal, R. 2011. PaperPhone: understanding the use of bend gestures in mobile devices with flexible electronic paper displays. *Proceedings of the ACM Conference on Human Factors in Computing Systems, CHI '11* (2011), 1303–1312.

[24] Lee, M. 2010. *Multimodal speech-gesture interaction with 3D objects in augmented reality environments*. University of Canterbury. Department of Computer Science and Software Engineering.

[25] Lee, S.-S., Kim, S., Jin, B., Choi, E., Kim, B., Jia, X., Kim, D. and Lee, K. 2010. How users manipulate deformable displays as input devices. *Proceedings of the ACM Conference on Human Factors in Computing Systems, CHI '10* (2010), 1647–1656.

[26] Lindeman, R.W., Sibert, J.L. and Hahn, J.K. 1999. Hand-held windows: towards effective 2D interaction in immersive virtual environments. *Proceedings of IEEE Virtual Reality* (1999), 205–212.

[27] Lindlbauer, D., Grønbæk, J.E., Birk, M., Halskov, K., Alexa, M. and Müller, J. 2016. Combining shape-changing interfaces and spatial augmented reality enables extended object appearance. *Proceedings of the ACM Conference on Human Factors in Computing Systems, CHI '16* (2016), 791–802.

[28] Massie, T.H. and Salisbury, J.K. 1994. The phantom haptic interface: a device for probing virtual objects. *Proceedings of the ASME* (1994), 295–300.

[29] Nakagaki, K., Follmer, S. and Ishii, H. 2015. LineFORM: actuated curve interfaces for display, interaction, and constraint. *Proceedings of the ACM Symposium on User Interface Software & Technology, UIST '15* (2015), 333–339.

[30] Ortega, F.R., Galvan, A., Tarre, K., Barreto, A., Rishe, N., Bernal, J., Balcazar, R. and Thomas, J.-L. 2017. Gesture elicitation for 3D travel via multi-touch and mid-air systems for procedurally generated pseudo-universe. *IEEE Symposium on 3D User Interfaces (3DUI)* (2017), 144–153.

[31] Perry, J.C., Rosen, J. and Burns, S. 2007. Upper-limb powered exoskeleton design. *IEEE/ASME transactions on mechatronics*. 12, 4 (2007), 408–417.

[32] Piumsomboon, T., Clark, A., Billinghurst, M. and Cockburn, A. 2013. User-defined gestures for augmented reality. *Extended Abstracts on Human Factors in Computing Systems, CHI-EA '13* (2013), 955–960.

[33] Ramakers, R., Schöning, J. and Luyten, K. 2014. Paddle: highly deformable mobile devices with physical controls. *Proceedings of the ACM conference on Human factors in computing systems, CHI '14* (2014), 2569–2578.

[34] Rendl, C., Kim, D., Fanello, S., Parzer, P., Rhemann, C., Taylor, J., Zirkl, M., Scheipl, G., Rothländer, T., Haller, M. and others 2014. FlexSense: a transparent self-sensing deformable surface. *Proceedings of the ACM symposium on User interface software and technology, UIST '14* (2014), 129–138.

[35] Sato, M. 2002. Development of string-based force display: SPIDAR. *VSMM* (2002).

[36] Simeone, A.L., Velloso, E. and Gellersen, H. 2015. Substitutional reality: Using the physical environment to design virtual reality experiences. *Proceedings of the ACM Conference on Human Factors in Computing Systems, CHI '15* (2015), 3307–3316.

[37] Slater, M. 2009. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 364, 1535 (2009), 3549–3557.

[38] Stoakley, R., Conway, M.J. and Pausch, R. 1995. Virtual reality on a WIM: interactive worlds in miniature. *Proceedings of the ACM Conference on Human Factors in Computing Systems, CHI '95* (1995), 265–272.

[39] Subramanian, S., Seah, S.A., Shinoda, H., Hoggan, E. and Corenthy, L. 2016. Mid-air haptics and displays: systems for un-instrumented mid-air interactions. *Extended Abstracts on Human Factors in Computing Systems, CHI-EA '16* (2016), 3446–3452.

[40] Teather, R.J., Natapov, D. and Jenkin, M. 2010. Evaluating haptic feedback in virtual environments using ISO 9241-9. *IEEE Virtual Reality*. (2010), 307–308.

[41] Vatavu, R.-D. and Wobbrock, J.O. 2015. Formalizing agreement analysis for elicitation studies. *Proceedings of the ACM Conference on Human Factors in Computing Systems, CHI '15*. (2015), 1325–1334.

[42] Wagner, J., Huot, S. and Mackay, W. 2012. BiTouch and BiPad: designing bimanual interaction for hand-held tablets. *Proceedings of the ACM Conference on Human Factors in Computing Systems, CHI '12* (2012), 2317–2326.

[43] Wobbrock, J.O., Aung, H.H., Rothrock, B. and Myers, B.A. 2005. Maximizing the guessability of symbolic input. *Extended Abstracts on Human Factors in Computing Systems, CHI-EA '05* (2005), 1869–1872.

[44] Wobbrock, J.O., Morris, M.R. and Wilson, A.D. 2009. User-defined gestures for surface computing. *Proceedings of the ACM Conference on Human Factors in Computing Systems, CHI '05* (New York, NY, USA, 2009), 1083–1092.

[45] Zenner, A. 2016. *Investigating Weight Distribution in Virtual Reality Proxy Interaction*. Saarland University & DFKI, Germany.

[46] Zenner, A. and Kruger, A. 2017. Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy. *IEEE Transactions on Visualization and Computer Graphics*. (2017), 1285–1294.