Big or Small, It's All in Your Head: Visuo-Haptic Illusion of Size-Change Using Finger-Repositioning

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ABSTRACT

Haptic perception of physical sizes increases the realism and immersion in Virtual Reality (VR). Prior work rendered sizes by exerting pressure on the user's fingertips or employing tangible, shape-changing devices. These interfaces are constrained by the physical shapes they can assume, making it challenging to simulate objects growing larger or smaller than the perceived size of the interface. Motivated by literature on pseudo-haptics describing the strong influence of visuals over haptic perception, this work investigates modulating the perception of size beyond this range. We developed a fixed-sized VR controller leveraging finger-repositioning to create a visuo-haptic illusion of dynamic size-change of handheld virtual objects. Through two user studies, we found that with an accompanying size-changing visual context, users can perceive virtual object sizes up to 44.2% smaller to 160.4% larger than the perceived size of the device. Without the accompanying visuals, a constant size (141.4% of device size) was perceived.

KEYWORDS

visuo-haptic perception, cross-modal integration, perceptual illusion, pseudo-haptics

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1 INTRODUCTION

Just as we naturally interact with objects of varying sizes in our everyday lives, Virtual Reality (VR) environments also present us with objects that either maintain static sizes or undergo dynamic size-changes. This dynamic resizing of objects, such as water hoses, bicep muscles, or small breathing creatures held in the hand, continuously provides haptic feedback regarding the object's status, enhancing the immersive experience in VR. Also, rendering the size-changes of magical props or tools commonly seen in games and entertainment contexts can immerse the user into fantasy VR worlds as well. To simulate different sizes of virtual objects, previous research has introduced various haptic interfaces. These interfaces either physically mimic the size of the virtual object [16, 41, 46] or utilize wearables [8, 9, 13] and exoskeletons [5, 17, 24] to restrict finger movements and simulate where the fingers would make contact with the virtual object.

However, each of these approaches has its own limitations when it comes to replicating the dynamic resizing of virtual objects. Most physical shape displays, for instance, struggle to replicate the changing size of objects held in the hand, as they must contend with the force of the user's grip [16]. On the other hand, wearables and exoskeletons that restrict finger movement face challenges as well. Passive wearables, such as those utilizing braking mechanisms, cannot effectively convey dynamically resizing objects [8, 9, 13, 38]. In contrast, active devices capable of this simulation tend to be heavy, power-intensive [10], and limited in the range of size changes they can render [46].

To address the above issues, we propose a different approach to rendering the dynamic size-change of handheld objects in VR: by neither changing the physical size of the device nor by resisting the user's grip, but instead using finger-repositioning to provide haptic cues in the hand. Using the finger-repositioning device we developed, we propose stimulating both the proprioceptive cues of finger joints and the tactile cues on the palm and volar side of the fingers, which users interpret, given an appropriate visual representation, as alteration of size of objects held in the hand. Based on this intuition, we propose an alternate approach to rendering virtual objects in the hand dynamically changing size in a wide range at relatively quick speeds.

The contribution of this work is three-fold:

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(1) We propose a novel approach for rendering size-change of virtual objects leveraging visuo-haptic illusion and corresponding finger-repositioning.
(2) We detail the design and implementation of a fixed-sized finger-repositioning controller.
(3) We conducted two user studies evaluating the effectiveness of the technique in rendering different sizes, first without a size-changing visual context (static visuals), followed by a study with a size-changing visual context (dynamic visuals).

To the best of our knowledge, the approach of rendering visuo-haptic size-change illusion via finger-repositioning has not been explored by prior work. We believe the findings from our studies can serve as an initial exploration of a more generalizable approach that enables various new interactions in the VR environment.

2 RELATED WORK

2.1 Shape/Size-Displays

To render the haptic feedback of various virtual object forms, prior works have explored the usage of shape-changing displays. Shape displays[32, 39] are devices that can generate dynamic shapes and surfaces, typically using a planar array of linearly-actuated pins that move up and down to create a 2.5D surface. In the attempt of reducing the size of table-top pin arrays, researchers have developed smaller handheld displays for shape rendering on the palm[46], index fingertip[2], and the edge of a mobile phone[22]. However, most shape displays remain bulky, complex, and limited in the area they can cover.

Several work attempted to create shape-displays to render objects of different sizes in the hand. X-Rings[16] has been designed as a shape display that extrudes surfaces 360 degrees around a central axis that can be grasped by the entire hand, but its capability to render a dynamic change of shape is limited. Inflatable bladders[5, 19, 35, 45] can render shapes in the user's hand. These bladders can render a few fixed shapes and different assistive forces by changing the air pressure. PuPoP[41] can change the rendering between a few fixed shapes by using multiple inflatable bladders, and the commercial HaptX device[18] covers the skin of the palm with tiny inflatable bubbles that can simulate the skin touching dynamic stimuli but not complete geometry. However, their use for dynamic real-time haptic sensations is limited by their need for an additional pneumatic or hydraulic pump and their few degrees of freedom.

Unlike prior shape-display works, we propose rendering various shapes not by changing the form of the interface itself, but by repositioning the fingers holding an interface with constant form. Our proposed approach has the advantage of not being limited by the actuation range of the device, but instead by the length of the user's fingers, allowing for maximizing the dynamic movement range of the fingers and the consequent range of expressible virtual object sizes.

2.2 Constraining Hand movement

A limitation of shape-displays rendering the full shape of a virtual object is that parts of the object that are not in touch with the user's skin are not sensed and therefore may not be worth the resources to render. As an alternate approach, haptic exoskeletons[4, 5, 9, 12, 13, 21, 24] provide kinesthetic feedback of rigid grasping using mechanical structures worn on the fingers, with most exoskeletons focusing on rendering at the fingertips. However, their primary drawback is their cumbersome form factor, which makes them difficult to wear and increases the potential for collisions with the user's environment.

Another approach is using a handheld controller that can limit the finger's motion and prevent them from closing on a virtual object or poking a finger into one. NormalTouch [2] uses a motorized platform that the index finger lies on, and whenever the finger penetrates a virtual object, it pushes the fingertip back outside the object. The CLAW controller [10], allows for applying force between the index finger and the thumb, representing a held object. CLAW uses a strong and heavy motor to be able to resist the forces applied by the user. Capstancrunch [38] replaces the motor with a brake. While improving the weight and power consumption of CLAW, it cannot change the angle between the fingers against the user's force. FingerX [42] uses an extending structure connected to each finger and can render grounded penetration prevention forces when the virtual objects lie close to physical surfaces such as a table. HapticBots [40] uses autonomous small robots that move along a physical surface such as a table and prevent fingertips from penetrating spaces occupied by virtual geometry.

Other controllers have been developed to render skin shear over fingertips [27, 44], and simulate grounded forces such as gravity [8], inertia [28, 37, 47], drag [48], or propulsion [20, 23]. While the user's hand may feel the touch of an object in different parts of the fingers and the palm, due to the mechanical complexity, most of these devices provide haptic feedback primarily to fingertips. In contrast, our approach leverages finger-repositioning and consequent proprioception and tactile cues over a large portion of the hand to create the sensation of objects with dynamically adjusted sizes held in the palm.

2.3 Pseudo-Haptics & Visuo-Haptic Illusion

The difficulty of rendering a large variation of shapes and the need to mold the shape against strong forces applied by the hand led us to look for a different way to convey the haptic sensation of virtual object's shape to the user, leveraging Pseudo-Haptics [30]. Existing shape-displays and haptic controllers have used a combination of a visual display that shows the desired motion and shape and a limited haptic display to improve the perception of the haptic experience. Abtahi et al. [1] used scaling and redirection of the user's hand for manipulating hand-eye coordination to extend the perceived resolution of a shape display, and Feick et al. [14] used similar techniques to map a fixed-sized mechanical slider to a variety of virtual sliders of different sizes and sliding speeds. Gonzalez et al. [16] mapped the limited dynamic range of the X-Rings shape display to objects of larger scale and geometry variation. All those examples use the limited output of the haptic display and enhance it using the dominance of visual sensing over the haptic sensations. Yet, they do assume that the device renders the shape, and that the user actually "feels" the haptic feedback [34].

A work conceptually close to the direction suggested in this work is TORC [31]. Instead of rendering the shape of an elastic object held between two fingers, as done by CLAW [10], it renders a different signal connected semantically to the motion. TORC rendered a vibrotactile cue triggered by the changing pressure applied by the fingers that approximate friction inside the object's material as pressure increases. The fusion of the visual stimuli showing an object deforming under pressure and the synchronized haptic vibrations generate a convincing experience of the object shape-changing. Yet, the lack of proprioceptive sensing of movement of the fingers holding the object prevents the experience from being complete. Our work differentiates from the above by focusing on the sensation from the combined tactile and proprioception stimuli to render different size-change effects based on the accompanying visual context.

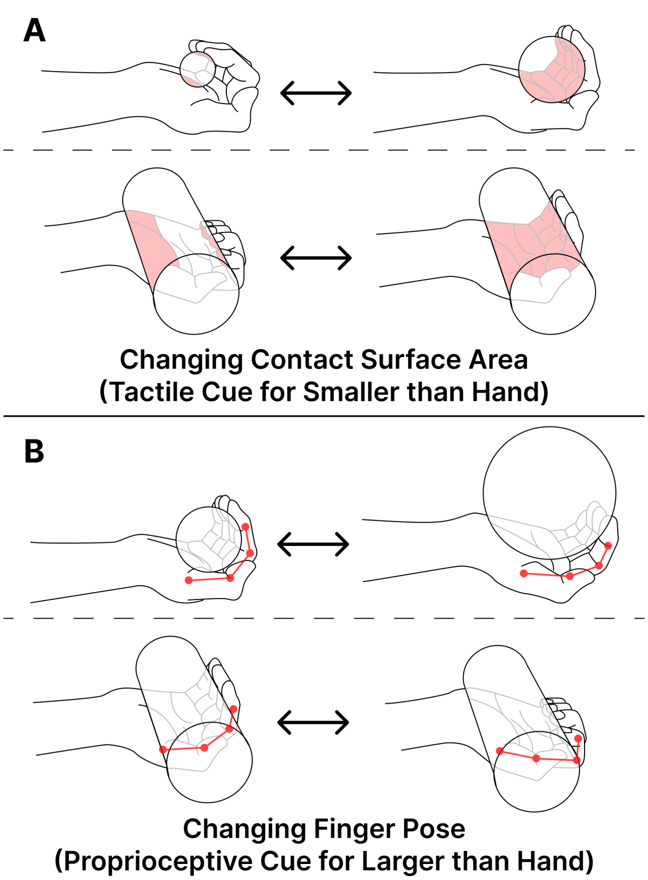

Figure 1: Analogy of ball of different sizes (top rows of A and B) mapped to proposed finger-repositioning technique (bottom rows of A and B). (A) Illustrates the variation in contact surface area when ball size is fitting or smaller than the hand, with corresponding finger-repositioning around a cylinder that produces similar cues. Likewise, (B) illustrates the variation in proprioceptive cues and corresponding finger-repositioning when the ball size is fitting or larger than the hand.

3 PROPOSED INTERACTION CONCEPT

When interacting with objects with your hands, multiple tactile, kinesthetic, and proprioceptive haptic cues simultaneously provide a holistic perception of the object and its properties.

For example, when gently gripping a rigid sphere in your hand, such as a cue ball from a pool table, as shown in Figure 1A, you can notice that with your fingers wrapping around the ball, it fills your grip completely, with large contact surface area in contact with your skin, providing tactile stimulation to the palm and fingers. Now keeping the fingertips in contact, if the cue ball were to slowly shrink into the size of a golf ball, one can notice that the ball no longer fills the inside of the grip completely, with less surface in contact with the skin, resulting in an increase of empty space in your hand. Conversely, if the cue ball increases into the size of a bowling ball Figure 1B, one can notice that the fingertips are pushed back and as the fingers extend backwards.

In the above example, we draw attention to two main haptic cues at play—tactile cues (surface contact) and proprioceptive cues (finger pose)—both causing a perception of size-change, but each applying to a different object size range (larger or smaller relative to the hand). Thus, we speculate that appropriate haptic cues within a visual context could obviate the necessity for physically altering an object's size to discern a size change when held in the hand.

For instance, consider the scenario depicted in Figure 1, where an individual grasps a cylinder of fixed dimensions. As the fingertips traverse the lateral surface of the cylinder, both the contact surface area and the finger orientation change, akin to a situation where the object itself undergoes a size alteration. Given the resemblance between the haptic feedback generated by this finger repositioning and that arising from an authentic size-altering object (Figure 1), we hypothesize that these cues can be mapped to visuals of the size-change of an object held in the hand, creating an illusion of size alterations.

Therefore, in this paper, instead of changing the size of the object itself or by limiting finger motion to match that of holding a given object, we propose a method for rendering size-change perception via finger-repositioning (i.e., wrapping and unwrapping fingers) using a hardware controller with rotating rings of a fixed size, while providing a consonant visual context in VR. To investigate our hypotheses, we developed two studies with two distinct objectives. In the first study, we investigate whether the proposed finger-repositioning method alone elicits the perception of size-change. In the second study, we investigate whether the range or start/end points of finger-repositioning affects the perceived size, when accompanied by visuals that provide a size-changing context.

4 DESIGN & IMPLEMENTATION

Following the cylinder example above, we propose a mechanism of a constant size that repositions the fingers to provide haptic cues that can be interpreted as size-change perception. Using four stacked rings that rotate around a common central axis held in the hand, the device repositions the index, middle, ring, and little fingers each around the central axis (Figure 3). As a result of repositioning, the tactile and proprioceptive cues of each finger are modulated. With appropriate visuals providing context, these cues can be interpreted as the size-change of the object in hand.

4.1 Finger-Repositioning System

The hardware of this prototype consists of three primary components: four rotating rings, a palm guard, and a VR tracker, as depicted in Figure 2. At its core, the device features four rings, stacked atop one another, all capable of rotation around a shared central axis within the core housing. This rotation is made possible by four bearings securely attached to the core housing for each ring. These bearings permit rotation exclusively around the central axis, ensuring smooth movement with minimal friction.

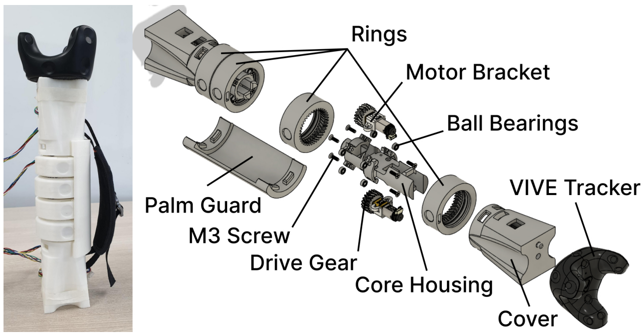

Figure 2: The finger-repositioning device (left). An exploded view of its assembled components (right).

The rings have a diameter of 55 millimeters and a width of 20 millimeters. Within each ring, a neodymium coin magnet, 10 millimeters in diameter and 3 millimeters thick, is securely fixed beneath the lateral surface at the midpoint. Additionally, a circular depression measuring 10 millimeters in diameter can be found on the lateral surface, directly above the underlying magnet. This design facilitates the placement of the user's fingertips.

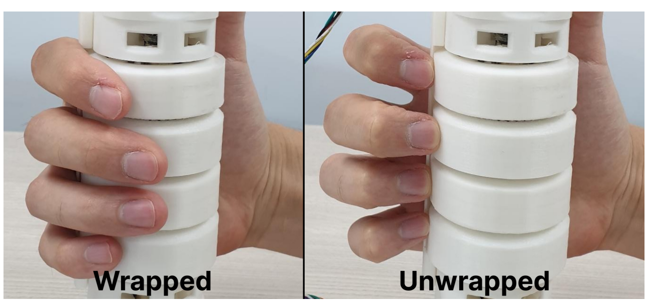

Figure 3: Example of finger-repositioning via ring mechanism, ranging from wrapped (left) to unwrapped (right) finger pose states.

To further enhance the user experience, a palm guard is incorporated into the device. This palm guard effectively prevents any unintended contact between the user's palm and the rotating rings, ensuring that undesired tactile cues are avoided when the device is held. It provides coverage over a surface spanning 150 degrees around the rings. An adjustable strap is used to secure the device firmly in the hand.

The motors responsible for driving this mechanism are the 1000:1 Micro Metal Gearmotor HP 6V with Extended Motor Shaft, while

Table 1: Hardware specifications

Property	Value
Weight (w/o VIVE tracker)	329 g (256 g)
Dimensions	$77 \times 70 \times 272$ mm
Ring Diameter	55 mm
Ring Height	20 mm
Motor Gear Ratio	986.41 : 1
Drive Gear to Ring Internal Gear Ratio	20 : 38
Encoder Counts per Revolution (CPR)	12
Magnet Slot Diameter	10 mm
Maximum Movement Range (Arc Length)	96.3 mm
Maximum Ring Rotation Speed Limit	6000 $QPPS$
Maximum Ring Revolutions per Minute	≈ 0.267 RPM
Maximum Ring Rotation Surface Speed	$\approx 46.1\,\mathrm{mm\,s^{-1}}$
Maximum Torque at Maximum Speed	$\approx 0.7\,\mathrm{N \cdot m}$

the Magnetic Encoder Pair Kit with Top-Entry Connector for Micro Metal Gearmotors, offering 12 CPR, effectively reads the motor's speed and position, contributing to precise control and feedback within the system. Internal gears leverage a herringbone gear teeth design for higher grip.

The driving motors are controlled with two RoboClaw 2x7A Motor Controllers[1], interface with Unity via a serial connection (460800 baudrate, maximum possible for the RoboClaw). Communicating with the RoboClaw controllers from Unity was done through the RoboClaw C# Class Library[2]. The built-in closed-loop position control of the RoboClaws was used to control the rings. The motor controllers were supplied with $7.5V$ through a DC-regulated power supply.

4.2 Technical Evaluation of Device

Real time motor position, speed, and current draw values are accessible through the RoboClaw controllers. However, to understand the *torque* applied on the user's fingers by the rings, a setup specifically for measuring motor stall torque was constructed (Figure 18).

The torque produced by a single ring was measured via a custom apparatus modified from the prototype. A three-axis force sensor (FSE103[3]) measured the torque of a custom lever arm extending $50mm$ from the center of the device. With the voltage fixed at $7.5V$, current was applied from $0.02A$ to $0.3A$ in $0.02A$ intervals. At each input current, 498 force measurements were recorded at 20 Hz sampling rate. To assess the *speed and responsiveness* of the rings, a ring was set to move 50 mm at 6000 quadrature pulses per second (QPPS) and its speed recorded at 120 Hz.

4.2.1 Results. The mean torque measurements in newton-meters of all three axes plotted against input current in amperes is shown

[1]https://www.basicmicro.com/Roboclaw-2x7A-Motor-Controller_p_55.html
[2]https://downloads.basicmicro.com/code/RoboclawClassLib.zip
[3]https://variense.com/product/fse103/

in Figure 4A. A linear trend line of $\tau = 1.9391I + 0.1378$ with $R^2 = 0.9918$ was observed. The recorded speed and position of the rings is shown in Figure 4B . The motor rise time was 277.1 ms.

Referring to PoCoPo [46] that operated against user's grip, the device could exert an output force of 2.5 N and move the pins at 4.67 mm s^{-1}. Our device delivered 0.43 N · m at 0.15 A, or 8.6 N. At a maximum of 0.30 A, the device can deliver up to 0.72 N · m or 14.4 N. The maximum speed of finger-repositioning as shown in Table 1 is 46.1 mm s^{-1}.

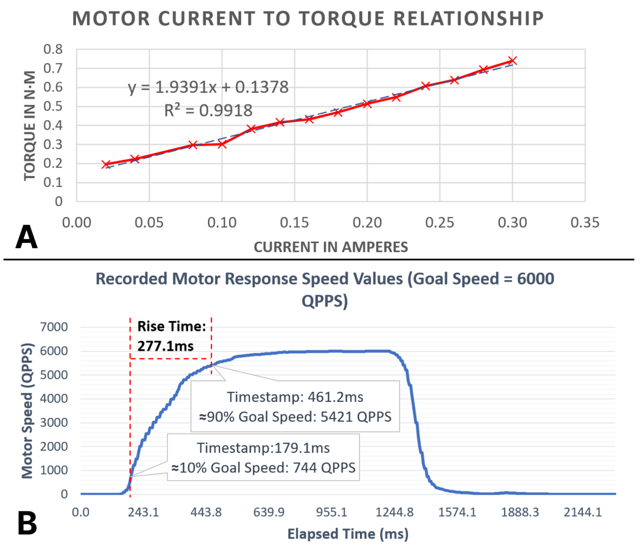

Figure 4: (A) The motor current-torque evaluation plot with dashed trend line. (B) Motor speed evaluation plot with annotated rise time.

These results combined suggest that our device is sufficiently responsive and strong for operation. The large torque value shows that the motors are unlikely to stop or slow their rotation during normal usage. Nonetheless, to prevent unintended surges of currents and motor damage due to mechanical blocking, a stall current limit of 0.15 A was set via a script.

5 USER STUDIES

We conducted two user studies to understand the effect of our proposed technique on virtual object size perception. In the first study, we investigated the effect of finger-repositioning *prior to* showing a static virtual object. In the second study, we investigated the effect of finger-repositioning *during* showing a size-changing virtual object.

5.1 Study 1: Perceived Size when Fingers are Repositioned Prior to Showing a Static Virtual Object

Our proposed technique involves finger-repositioning while providing an accompanying visual context. However, as prior works have well-demonstrated the effects of visual dominance over haptic sensation when determining sizes [3, 43], we found the need to first investigate whether finger-repositioning alone without an accompanying visual context elicits size-change perception. Due to the need of measuring participants' perceived size data, we used visuals of a virtual cylinder to which the participants were to compare the size they perceived with their repositioned fingers. However, we designed Study 1 to always reposition the participant's fingers *before* showing the virtual object and asking for a size judgement. Study 1 therefore determines the perceived size of the virtual object immediately subsequent to different finger-repositioning conditions.

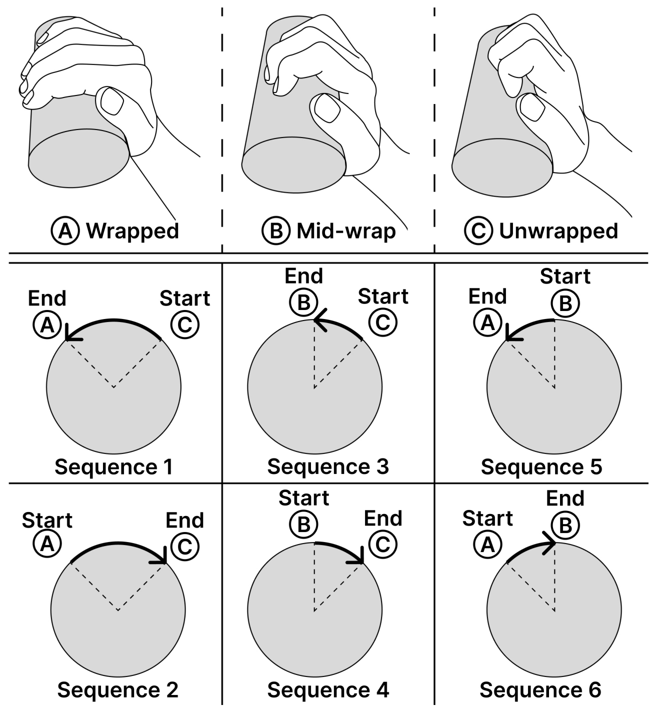

Figure 5: Finger start/end points and finger-repositioning sequences. Three start/end points were defined (top row): (A) Wrapped, (B) Mid-wrap, and (C) Unwrapped. Six sequences with different start/end point combinations were defined (bottom rows). Sequence diagrams are illustrated as if viewing the prototype held in the right hand from the top.

5.1.1 Experimental Design.

To limit the variations of finger-repositioning conditions to investigate, we first defined three possible start/end points (Figure 5): *Wrapped*, *Unwrapped*, and *Mid-wrap*, each corresponding to the two ends of the finger-repositioning range and the midpoint in-between. We then defined six finger-repositioning sequences based on different combinations (3×2) of start and end points.

Following prior shape-display works [41, 46], the one-up-one-down double-random adaptive staircase method [25] was used to determine the visual size acceptance range (i.e. the range of visual sizes that are perceived as equal to the size perceived through haptic senses) for each finger-repositioning sequence. Staircase parameters of initial visual cylinder diameters based on device

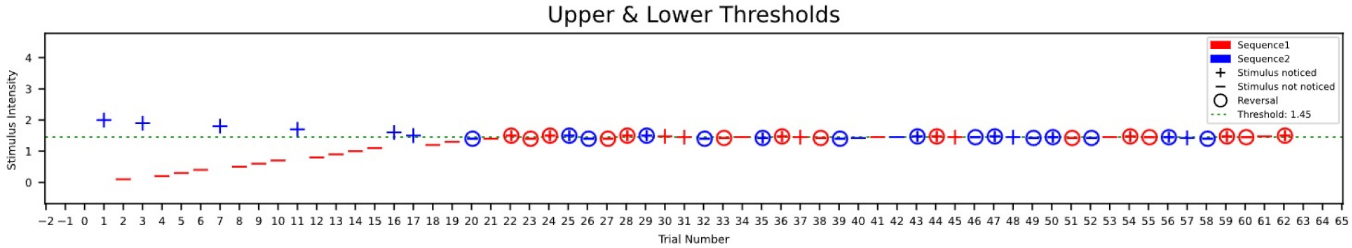

Figure 6: An example of a double-random staircase response by P7 for Sequence 4, seen to converge at 1.45 (79.75 mm) or 145% of the physical size (55 mm).

diameter (200%, 10%), step sizes (10%, 5%, 2.5%), and reversal counts (15 total, mean of last 5 as threshold) were closely followed, as seen in Figure 6. For each finger-repositioning sequence, a pair of ascending and descending staircases were run, for a total of six staircase pairs. Each sequence was presented in randomized order. The Unity Staircase Procedure Toolkit [49] was used to implement the staircases (Figure 6).

5.1.2 Participants. 12 participants (8 male, 4 female) between age 18 to 31 (Mean = 22.6, SD = 4.1) were recruited for the study. All participants were right-handed. For two of the participants, it was their first VR experience, while the rest of the participants had non-regular, intermittent experiences using VR. After the study, participants were compensated with the equivalent of USD 11 in local currency.

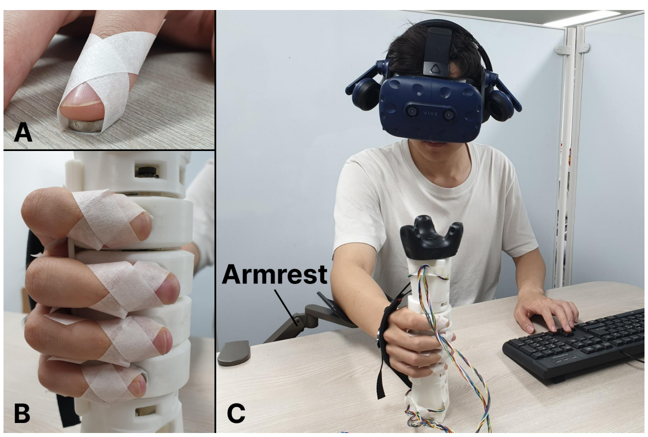

Figure 7: (A) Closeup of magnet taped to fingertip. (B) Each finger taped and fixated to a ring via magnets. (C) Study setup for Study 1 & Study 2.

5.1.3 Procedures. Participants were informed that they would be using a "device that can express different sizes" which will hidden from view until the end of the study. In order to ensure the fingers are always at a known position during the study, neodymium magnets were taped to each fingertip excluding the thumb (Figure 7). The experimenter then aided the participant to first wear the head-mounted display (HMD) then the finger-repositioning device on the participant's dominant hand. To account for different finger lengths of participants, the device was calibrated before each study so that all fingers would completely wrap around the device. The distance between the *Wrapped* and *Unwrapped* positions of the little (shortest) finger (Mean = 26.6 mm, SD = 6.2 mm) was set as the repositioning distance range of each finger.

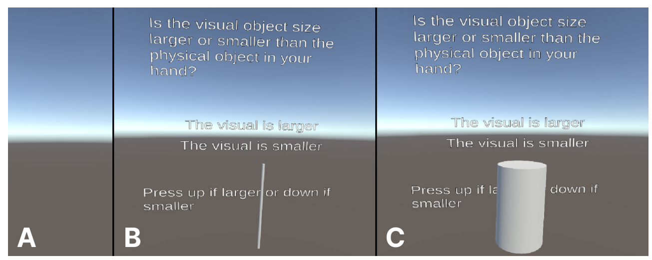

Figure 8: Study 1 VR Environment. (A) The blank scene shown during finger-repositioning. The prompt and initial cylinder sizes for the (B) ascending and (C) descending staircases, respectively.

In each study trial, participant were first shown a blank VR scene (Figure 8A) while their fingers were repositioned to the start point of the sequence in one second. Afterwards, the fingers were repositioned to the end point in one second. After the fingers were repositioned, a virtual cylinder was shown with a text prompt asking, "Is the visual object size larger or smaller than the physical object in your hand?" (Figure 8B-C) Participants could respond with "The visual is larger" or "The visual is smaller" through the keyboard using their left hand. After their response, the next trial began. Upon completion of all trials of the staircase pair, the next sequence was presented.

Participants practiced the procedure with a random sequence for a few reversals before beginning the first study sequence. As done in prior works [41, 46], no virtual hand was shown during the trials. Unlike prior works, because our device repositions the fingers for each trial, noise-cancelling headphones (Sony WH-1000XM4) playing white noise[4] were worn by participants to mask device operation sounds. Each staircase took around five minutes to complete.

5.1.4 Results & Discussion. Table 2 shows the visual size acceptance thresholds for both ascending and descending staircases per

[4] https://youtu.be/2y6zdAbN9o8?si=4bEXn9qdfefxFavo

Table 2: Visual size acceptance range (n=12) in relation to physical size (55 mm) reported in millimeters with standard error (SE).

Haptic Condition	Sequence 1	Sequence 2	Sequence 3	Sequence 4	Sequence 5	Sequence 6
Ascending Staircase Threshold	79.865 mm	80.919 mm	76.977 mm	75.946 mm	75.350 mm	80.850 mm
(Standard Error)	(4.374 mm)	(6.131 mm)	(5.077 mm)	(4.988 mm)	(3.696 mm)	(4.943 mm)
Relative Size Ratio	145.2%	147.1%	140.0%	138.1%	137.0%	147.0%
Descending Staircase Threshold	79.223 mm	79.200 mm	75.992 mm	75.442 mm	73.471 mm	80.140 mm
(Standard Error)	(3.735 mm)	(5.224 mm)	(4.828 mm)	(5.085 mm)	(3.352 mm)	(5.010 mm)
Relative Size Ratio	144.0%	144.0%	138.2%	137.2%	133.6%	145.7%

each finger-repositioning sequence. From the results, two key observations were made:

Firstly, the ascending and descending staircase thresholds are each on average 42.4% and 40.4% larger than the device, respectively. Participants always perceived the device to be about 40% larger than its size. This size estimation is close to what we expected and inline with prior works [41, 46] which also found that both the lower and the upper bounds of visual size acceptance to be larger than the device for cylindrical objects. Additionally, we found that the difference between the upper and lower thresholds (2.00%) is consistent with prior work with a rigid interface (6.0%) [46] but considerably smaller than a compliant interface (32.7%) [41].

Secondly, a repeated measures ANOVA with a Greenhouse-Geisser correction determined that the visual size thresholds did not differ statistically significantly between finger-repositioning sequences ($F(2.963, 32.591) = 0.089$, $p = .472$). This indicated that regardless of the finger-repositioning sequence, participants consistently perceived the device to be the same size.

From the above observations, seeing that participants always perceived the device to be about 40% larger than its size regardless of finger-repositioning sequence, we concluded that the haptic cues from finger-repositioning with the device alone is not capable of instilling the illusion of varying sizes, at least if virtual objects are shown after the fingers have completed repositioning. Referring to prior work in Pseudo-Haptic Feedback [33], a *visual feedback synchronized with sensorimotor action during simulation* is required to create a *coherent* representation of the environment from an *incoherent* set of real-time visual and haptic stimuli—in our case, the finger-repositioning mapped to the visual size-change. Therefore, similar to prior works extending the perceived dynamic range and speed beyond the physical limits of device via visual cues [7, 14], we also propose providing an accompanying visual context of size-change that is synchronized with finger-repositioning to elicit a visuo-haptic perception of size-change. We investigate this pseudo-haptic effect in Study 2.

5.2 Study 2: Perceived Size when Fingers are Repositioned During Showing a Size-Changing Virtual Object

In Study 2, we aimed to investigate whether by leveraging visuo-haptic illusion, the device can render the various sizes of a size-changing virtual object. We achieved this by introducing an accompanying visual context that enables finger-repositioning to be interpreted as size-change. Study 2 was therefore designed to determine the perceived size of a virtual object when an accompanying size-changing visual context is shown during finger-repositioning.

5.2.1 Experimental Design. To facilitate investigating the effect of accompanying visuals *during* finger-repositioning on size-perception, we designed Study 2 to have prolonged trials to allow users to constantly compare perceived visual sizes with haptic sizes. Therefore unlike Study 1 involving single finger-repositioning sequences, we defined three *compound* sequences of finger-repositioning that can be looped continuously as necessary. Following our proposed analogy of object sizes (Figure 1), three compound finger-repositioning sequences were defined as shown in Figure 9. Visually, a Size-Changing cylinder was shown instead of the static cylinder in Study 1.

In order to measure and compare sizes perceived through continuously size-changing visuals and continuously repositioning fingers, we defined three reference points at which the visual size-change and finger-repositioning will pause briefly. These reference points are shown as cylinders of different sizes in Figure 9. To adjust these reference points, we implemented three reference cylinders in the study environment (Figure 10) whose size the participant can adjust. The white size-changing cylinder repeatedly assumes the size of each reference cylinder sequentially (Figure 10A-C). Therefore, adjusting the reference cylinder sizes in turn changes the Size-Changing cylinder's sizes, and the method of adjustment [25] was used to determine the perceived size of the device during different finger-repositioning conditions.

The three reference cylinder sizes were set to be 50%, 150%, and 250% of the diameter of the device (55 mm) at the beginning of each trial. These sizes are based on the initial sizes (200%, 10%) and perceived device size (141.4%) from Study 1. Considering that the initial small size of Study 1 was excessively small as shown in the ascending staircase of Figure 6, the smaller reference cylinder was set to 50% while the larger set to 250%. The Middle reference cylinder was rounded to 150%.

Following our proposed analogy (Figure 1), an animated hand holding a size-changing cylinder was prepared to provide a mental reference point of how the size-changing cylinder is expected to be held in the hand (Figure 11). This animation was shown only once, without any finger-repositioning, during the introduction of the study procedure. As shown in Figure 11A-C, a small section and large section were defined, each corresponding to the two different object size ranges their corresponding haptic cues. During the study,

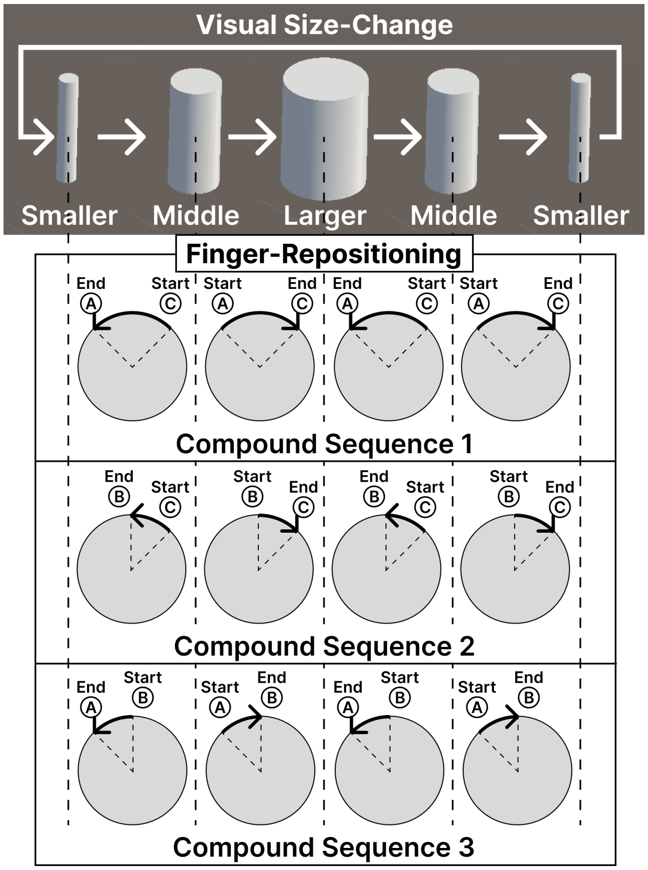

Figure 9: The three compound finger-repositioning sequences mapped to visual size-changes. The top row illustrates the size states the Size-Changing cylinder transitions through to complete one cycle. The remaining rows show the corresponding finger-repositioning during the visual transitions for each compound sequence.

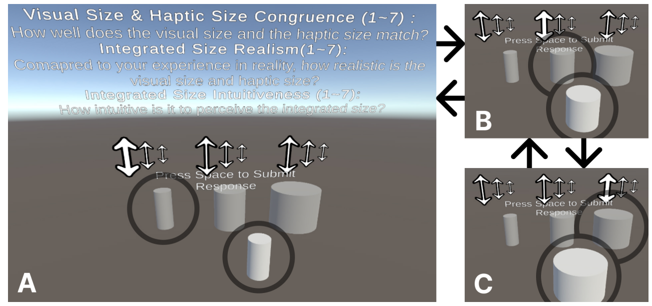

Figure 10: Study 2 VR environment. (A) Text prompts, three sets of selection arrows, three gray translucent reference cylinders, and a white solid Size-Changing cylinder are in view. The Size-Changing cylinder gradually assumes the size of the (A) Smaller, (B) Middle, and (C) Larger cylinders repeatedly.

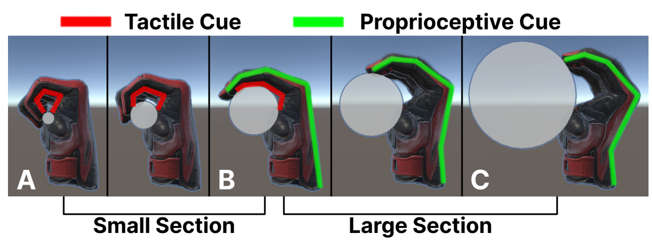

Figure 11: Hand animation frames with annotation of relevant haptic cues. Cylinder size range between the (A) smallest size and (B) middle size is denoted as the "small section". The range between (B) middle size and (C) largest size is denoted as the "large section". No annotations were shown to study participants. The virtual hand was only shown during study introduction and was removed for the study trials.

participant congruence and realism ratings were collected for each section separately.

During pilot studies, in addition to the compound sequences, we tested a "no finger-repositioning" condition. However, we found that participants adjusted all three reference cylinders to be the same size as no change was perceived through the fingers. Therefore, we removed this control condition from the main study. Each compound sequence was presented three times in random order, for nine total trials.

5.2.2 Participants. 12 Participants (all right-handed; 10 male, 2 female; age range 20 to 29, mean = 22.4, SD = 2.5) were recruited. In terms of prior VR experience, one owned a VR headset, four never experienced VR before, and seven had intermittent VR experiences ranging from one month to five years ago. After the study, participants were compensated with the equivalent of USD 11 in local currency.

5.2.3 Procedures. Study preparation, setup (Figure 7) and calibration procedures (Mean = 29.1 mm, SD = 5.7 mm) were identical to that of Study 1. As a key difference, the animated hand (Figure 11) was shown once as a mental reference point during study introduction. The hand was not shown during the study trials, as done by prior works [41, 46].

In each trial, participants were shown a white size-changing cylinder and three gray translucent reference cylinders (Figure 10). The Size-Changing cylinder was shown repeatedly and gradually assuming the size of each of the three reference cylinders, one at a time, at one second intervals with half second pauses in between. In sync with the Size-Changing cylinder, participant fingers were repositioned according to the compound sequence tested (Figure 9).

Participants were asked to adjust the size of each of the reference cylinders so that during the brief pauses, the Size-Changing cylinder matched the size perceived with their fingers as closely as possible. They were instructed to adjust the Middle cylinder first, before moving on to the smaller or larger cylinders or later returning for additional adjustments. Using the arrow keys on the keyboard, participants could select and adjust reference cylinder sizes in 10%, 5% or 2.5% increments (following the staircase step sizes of Study 1).

Table 3: Visual size acceptance range (n=12) with synchronized visuals in relation to physical size (55 mm) reported in millimeters with standard error.

Condition	Compound Sequence 1			Compound Sequence 2			Compound Sequence 3		
Visual Size	Smaller	Middle	Larger	Smaller	Middle	Larger	Smaller	Middle	Larger
Mean Size	52.67 mm	111.18 mm	181.23 mm	51.56 mm	96.36 mm	155.80 mm	56.22 mm	106.64 mm	160.95 mm
(Standard Error)	(4.97 mm)	(6.45 mm)	(11.99 mm)	(6.59 mm)	(6.12 mm)	(9.97 mm)	(5.19 mm)	(6.35 mm)	(9.80 mm)
Relative Size Ratio	95.8%	202.2%	329.5%	93.7%	175.2%	283.3%	102.2%	193.9%	292.6%

When participants indicated that they were satisfied with their adjustments, the reference and Size-Changing cylinders were hidden and the device was stopped. Participants were asked to provide a score from 1 to 7 on the perceived visuo-haptic congruence and realism following the examples in previous works [27, 44] for each the small and large sections as indicated in Figure 11. The prompt for visuo-haptic congruence rating was "How well does the visual size and the haptic size match? For perceived realism, the prompt was, "Compared to your experience in reality, how realistic is the virtual size and haptic size?" After the experimenter recorded the scores, the next trial was presented.

Three practice rounds, one with each compound sequence, were presented in balanced order before beginning the first study trial. The total study duration was around one hour on average.

5.2.4 Results. Table 3 shows the perceived size of the three reference cylinders for each compound sequence.

Quantitative Results. In sum, our results show four key findings: First, it is observed that on average, the Smaller cylinder (97.2%) was perceived as 2.8% smaller than the device (55 mm), whereas the Middle (190.4%) and Larger (301.8%) cylinders were each 90.43% and 201.8% larger than the device, respectively. Compared to the average perceived size of the device from Study 1 (141.4%), the device has shown to render sizes up to 44.2% smaller (97.2%) to 160.4% larger (301.8%). Interestingly, the Middle cylinder size (190.4%) was on average 49.0% larger than the perceived device size of Study 1 (141.4%). It appears that all three reference cylinders were increased by around 50% of their initial sizes on average. However, as many factors affect size-perception, further investigation into not only different initial sizes, but also the rate of size change, the length of pauses between transitions, the number of reference objects, etc. would be necessary to identify the potential cause of this phenomenon.

Second, the Middle cylinder was perceived significantly larger for Compound Sequence 1 (Mean = 202.2%) than for Compound Sequence 2 (Mean = 175.2%). A repeated measures ANOVA with a Greenhouse-Geisser correction determined that there was a statistically significant interaction effect between compound finger-repositioning sequence and reference cylinder sizes ($F(2.635, 28.983) = 7.212$, p = .001). A separate repeated measures ANOVA by reference cylinder size determined no significant effect of compound finger-repositioning sequence on Smaller cylinder size ($F(1.768, 19.444) = 1.002$, $p = .376$), but a significant effect on Middle ($F(1.929, 21.216) = 7.136$, $p = .005$) and Larger cylinder sizes ($F(1.984, 21.825) = 12.719$, $p < .001$). Post-hoc analysis with a Bonferroni adjustment revealed thatfor Middle cylinder sizes, Compound Sequence 1 was statistically significantly larger than Compound Sequence 2 (0.269(95% CI [0.056, 0.483]), $p = .013$), but not than Compound Sequence 3 (0.083(95% CI [-0.108, 0.268]), $p = .705$). The difference between Compound Sequence 2 and Compound Sequence 3 was also non-significant.

Third, the larger cylinder was perceived significantly larger for Compound Sequence 1 (Mean = 329.5%) than both Compound Sequence 2 (Mean = 283.3%) and Compound Sequence 3 (Mean = 292.7%). Post-hoc analysis for the Larger cylinder size revealed that Compound Sequence 1 was statistically significantly larger than both Compound Sequence 2 (0.462(95% CI [0.181, 0.744]), $p = .002$) and Compound Sequence 3 (0.369(95% CI [0.092, 0.645]), $p = .009$). Again, the difference between Compound Sequence 2 and Compound Sequence 3 was non-significant.

And fourth, there was no significant difference in perceived visuo-haptic congruence nor realism between the compound sequences tested. A Friedman test indicated there was no significant difference in congruence nor realism in either of the two size sections between compound finger-repositioning sequences. (Congruence in Large Section: ($\chi^2(2) = 4.826$, $p = .090$); Congruence in Small Section: ($\chi^2(2) = 3.200$, $p = .202$); Realism in Large Section: ($\chi^2(2) = 4.000$, $p = .135$); Realism in Small Section: ($\chi^2(2) = 5.105$, $p = .078$).

Qualitative Feedback. Some notable participant feedback on the study have been seen to support the findings above: In terms of differences perceived between finger-repositioning sequences, P5 and P7 described Compound Sequence 2 to be less convincing as for the Middle cylinder, the haptic sensation does not "completely fill the hand," as shown in Figure 11. Similar opinions that Compound Sequence 2 was less convincing than the other two sequences were shared by P4, P6, P9, and P10, although participants had difficulty describing the cause of this perception. We speculate that this may be due to the finger-repositioning of Compound Sequence 2 not completely align with the mental reference point (Figure 11) shown prior to the study. Further investigation with different mental reference points to validate this speculation would be an interesting line of future work.

When the device was shown after the study, although most participants described the device's form and mechanism to align with their expectations, three participants (P12, P10, P3) expressed surprise and fascination that the prototype was of a constant size. As P10 shared, "I could not imagine that this (device) kept a constant size throughout the experiment. In my head, I thought that the object was actually changing sizes. But now I see that it's actually constant size, and that's quite surprising." Their responses indicated that in some cases, it was possible to create a convincingly realistic experience of size-change in the hand via finger-repositioning. Identifying the factors that caused the above cases would serve as valuable future work for visuo-haptic illusion interactions.

Summary. Our results suggest that size-change can be perceived via finger-repositioning when an accompanying visual context is shown and that the haptic perception of size is impacted by two variables: the degree of a proprioception stimuli, and the contact area of tactile stimulation. Specifically, for the Middle cylinder, more contact surface area is perceived as a larger object, and for the Larger cylinder, more finger curling is also perceived as a larger object. The results reflect literature in pseudo-haptic feedback [33] and works showing the influence of both tactile and proprioceptive cues on object size perception [11, 36]. We detail the implications and considerations about our proposed approach in our Discussion.

6 APPLICATIONS

In this section, we showcase three categories of VR applications that demonstrate how our proposed finger-repositioning technique can be employed to simulate objects with changing sizes over time or be mapped to a different aspect beyond size.

6.1 Applications Based on Reality

In everyday settings, there are not many instances of objects changing size. However, we introduce the following applications as possible cases which are part of a larger body of interactions to which our proposed technique may be applied.

6.1.1 Fire Hydrant. Size-change perception can intuitively communicate the status of an object during interaction. In this scenario (Figure 12), the user's virtual left hand holds the hose attached to a fire hydrant. As the right hand turns the pressure valve, the diameter of the hose increases or decreases proportionally to the change in pressure within the hose as pressurized water flows through it. This dynamic adaptation of the diameter of the hose allows the user to have a haptic sense of how much water is flowing, without looking at the pressure gauge or keeping track of how much the valve has been turned. We envision this interaction to be applicable to various flexible tubing or containers that transfer or store fluids as well.

Figure 12: The Fire Hydrant demo. The hose is held in one hand while the valve is turned with the other. The hose thickness and pressure gauge value change with valve rotation. The hose is held instead of the nozzle to demonstrate the concept. In practice, we expect one hand to hold the nozzle while the other hand holds the hose.

6.1.2 Flexing and Relaxing Bicep. Many organic objects naturally modulate between different sizes in response to physical actions. In this scenario (Figure 13), the virtual hand holds the bicep muscle. As the user bends or extends their other arm, the muscle expands or contracts proportionally to the angle of the arm. Through sensing the size of the bicep, the user is able to understand the degree of muscular expansion and contraction corresponding to the arm's movement. In addition to muscle movement, such modulating sizes can be expected in various other organic contexts as well, such as holding a breathing living creature in the hand or a creature in the hand gaining or losing weight due to feeding or exercising, respectively.

Figure 13: Bicep Flexing and Relaxing demo. As the arm is flexed and relaxed, the bicep expands and contracts, and the change in thickness of the upper arm is felt with the other hand.

6.2 Applications Based on In-Game Experiences

Our proposed technique especially shines in fantasy magical contexts that are often depicted in games and entertainment. In such contexts, a handheld object changes its size and form in a way that is not physically possible in reality. We introduce two such cases that represent a larger body of contexts and interactions to which our proposed technique may be applied effectively:

6.2.1 Object Power-ups and Power-downs. The concept of enhancing a tool's ability through upgrades or power-ups can be commonly seen in many game titles and entertainment content. In this scenario (Figure 14), the virtual hand holds a default battle axe. Upon consuming a power-up or upgrade, the battle axe increases in size and transforms into a tougher material, which enhances the range, potency, and durability of the weapon. Similarly, when becoming affected by a debilitating spell, the battle axe decreases in size and transform to a weaker material. By visually and haptically perceiving such changes to weapons due to temporary or permanent in-game effects, the user can experience higher immersion during game play.

6.2.2 Morphing Object to Switch from One Object to Another. In role-playing games, players often can switch between multiple tools with different functions. In this scenario (Figure 15), the virtual hand holds a staff that can transmute into another tool at will. The user can feel the staff's handle thicken in real time as it transmutes into a spear. The spear can then transmute into a mace or back to the staff, during which the user can feel the handle grow thicker or thinner, respectively. Through the transitions between different handle thickness, the user can experience wielding and switching

Figure 14: Power-up and Power-down demo. The normal-sized bronze battle axe (left) can power-up into a gigantic one of enchanted material (center). Similarly, the battle axe can power-down into a small size made of iron material (right).

between potentially any handheld object with a cylindrical handle within the size range our approach can render.

Figure 15: Morphing Between Tools demo. The (A) staff can (B) morph into a (C) spear, which can also (D) morph into a (E) mace.

6.3 Alternative Application Direction

The ability to render the size of an object can have uses that extend beyond the size-change semantic.

6.3.1 Weighted Rope. As VR is a space where the user lacks a lot of the physical feedback they are familiar with in the real world, any haptic rendering can be used for multiple purposes. In this case (Figure 16), a hand is holding a rope with a weight attached. When the weight is increased, the width of the rope decreases proportionally. The width of the the rope represents the force applied to it and can communicate to the user how close it is to snapping from being overloaded. Here, the haptic feedback has two functions: First, it is used to represent a constant grounded pulling force on the rope that a hand-held vibrotactile controller may not render to the user. Second, it communicates the status of the rope while the user may be looking at another object, such as a climbing target.

7 DISCUSSION

Finger-Repositioning & Synchronized Visuals. Prior works that limit hand and finger postures to render object sizes [8, 9, 12] vary the distance between the thumb and opposing fingers to render object sizes. We however, proposed repositioning the fingers in an unconventional way around a cylinder and therefore first explored whether the finger-repositioning by itself is associated with size-change. Although the results of Study 1 did not indicate any perceived size-change, in Study 2 size-change perception was observed

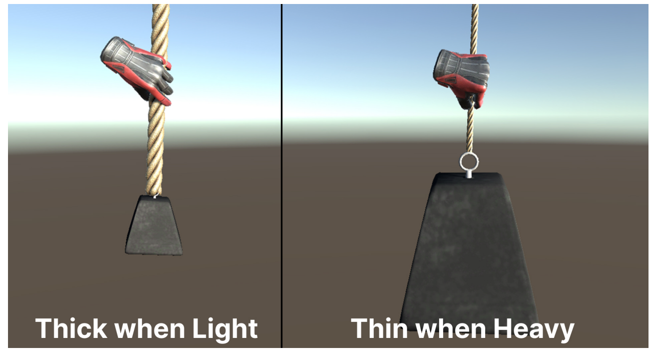

Figure 16: Weighted Rope demo. The rope held in the hand becomes thinner or thicker proportionally to the load applied.

with the provided accompanying size-changing visual context. This enabling of size-change perception through visual feedback is in line with work in Pseudo-Haptic Feedback [33], that describe the effect as the creation of a coherent perception from two incoherent yet synchronized visual and haptic stimuli. The haptic property can be different from what one could expect in the physical environment, but because the perceived sensation is dependent on the visual stimuli, it can be interpreted as an entirely new context accordingly. Prior works have leveraged this effect to extend the perceived dynamic range and speed of interfaces beyond their physical limits via visual cues [7, 14]. In our case, the haptic cues from finger-repositioning were seen to be successfully interpreted as size-change in Study 2 as a pseudo-haptic effect.

Same Set of Haptic Cues for Two Opposing Visual Effects. Related to the point above, one core aspect of our proposed technique is the repurposing of a single set of haptic cues resulting from finger-repositioning for eliciting the perception of two opposing perceptual effects (size-increase vs size-decrease). Considering the influence of tactile and proprioceptive cues in size-judgements [11, 36], in the observation of these cues involved in perceiving the size of a growing or shrinking object in the hand (Figure 1), we observed that one type of haptic cue is more involved than the other, depending on the object's size relative to the hand. From the observation, we proposed that instead of actively providing one haptic cue in place of the other for different object size ranges, we could provide both haptic cues at the same time but visually draw attention to one cue over the other, depending on the size range involved. Such approach would enable manipulating user haptic perception to perceive various aspects of virtual object properties via visual interventions, rather than by complex electro-mechanical means. The approach would be akin to pseudo-haptic feedback [33] where possibly incoherent haptic and visual cues create a coherent perception depending on the visuals given. We can envision future work in this direction to involve the development of non-specific haptic feedback devices [15], that can modulate tactile, kinesthetic, and proprioceptive cues that can be visually mapped to a wide range of haptic perception and applications (e.g. size, texture, weight, etc.). This direction is especially suitable for virtual environments, that can provide immersive, first-person, spatiotemporally synchronized visual cues.

Effect of Visual Dominance Over Haptic Perception. Past works have demonstrated the dominance of the visual senses in visuo-haptic perceptions [3, 43]. Literature in VR haptic interfaces have also acknowledged this phenomenon and have taken measures to address this in study design [41, 46]. We too have designed Study 1 to account for this effect, to make sure that the visual and haptic cues were presented separately as an initial step. We demonstrated that finger-repositioning rendered by the device alone does not cause size-change perception. However, with the addition of an accompanying visual context in Study 2, the relevant haptic cues were shown to be interpreted as size-change. Although it is true that for our proposed visuo-haptic illusion approach to be effective, accompanying visual context is certainly required, we believe this does not indicate that any alternate haptic feedback (e.g. vibrotactile, thermal, etc.) can achieve the same effect. Following our proposed analogy (Figure 1), we designed the mental reference point (Figure 11) to account for the natural haptic cues involved in holding objects of different sizes. Although vibration has been shown to affect weight perception [8, 26], as the perception of vibration is not directly associated with size, we do not expect vibrotactile feedback to be able to represent size-change directly, in the manner we proposed; if participants map stronger vibration to visuals of larger objects, it is expected to be interpreted as "a bigger mass of *vibrating material*." Similarly, temperature has been shown to affect perceived weight [6, 29] but is not expected to represent sizes directly; if larger objects are mapped to warmer temperatures, it is expected to be interpreted as "more mass of *warmer material*." As described above, although we expect mapping such alternate haptic feedback to size-changes to be possible, we also expect it to require an additional step of interpretation, resulting in a percept of the virtual object possessing the additional haptic property of interest (e.g. vibration or temperature).

Enabling Interactions of Size-Transitions. The key difference of our proposed approach from prior VR shape-display works [16, 41, 46] is that prior works physically changed their forms to assume the size or shape of different objects, and visual counterpart is not necessary to maintain the perception of the object's form. In other words, these approaches can be seen as focusing on replicating different *end state* forms. In particular, the key difference from X-Rings [16] is that X-Rings can render different shapes through its physical rearrangement of pins but is not capable of rendering the shape-changes *while* the user is holding the device, as it was not designed to counteract user grip forces. Therefore in terms of interaction, users are required to release their grip each time to allow the device to assume a different shape. To overcome this practical limitation, the authors have presented a use case scenario that involves the device assuming a target shape *before* the user grips the device, as the user's hand is approaching the target virtual object. Unlike X-Rings, our proposed approach was designed to render size-changes *while gripped* by the user and does not require releasing the device to render different sizes. Therefore, new interactions of dynamic object transformations and transmutations in the hand are possible, as shown through our proposed applications.

8 LIMITATIONS

Our work presents also some limitations and opportunities for improvement in future research.

Persistence of Visuo-Haptic Illusion. One of the key limitations of our proposed method is a strong reliance on visual cues to provide a context of size-change. As described by P4 in Study 2. when the participant turned their head to focus on resizing the reference cylinders with the animated cylinder out of their field of view, immediately they were unable to tell whether the animated cylinder was growing or shrinking in the hand. To prevent this breaking of the visuo-haptic illusion, a constant cue consistent with the finger-repositioning is required. Aside from always keeping the cylinder within the field-of-view (FOV), one approach can be to pause the finger-repositioning once the animated size-changing object is outside the FOV, which may allow to maintain a percept of the changed size of the object in the user's memory until the hand is back within the FOV. Another possible approach could be using alternate sensory cues (e.g. audio or haptic at a different site) to provide a size-changing context even when the object is outside the FOV. In terms of application, bimanual interactions that require both hands to be in close proximity to each other within the FOV, as the Fire Hydrant example Figure 12, may not encounter this issue. Exploration of techniques to overcome this practical limitation specific to visuo-haptic illusions would be an interesting topic for future work.

Finger-Repositioning Hardware. One limitations of the current finger-positioning mechanism is its limited degree of freedom. Increasing freedom in which the hand and fingers could be moved would allow for new potential applications for this technique in various interaction contexts, enabling experiencing changes in object form in multiple axes. Another inherent challenge arises from the necessity to switch motor directions when transitioning between smaller-than-hand and larger-than-hand contexts. Although this has been mitigated via brief pauses in the size-changing animation, future investigations could delve into feedback mechanisms and interaction scenarios characterized by gradual and seamless transitions, avoiding abrupt shifts.

Alternate Mental Reference Points or Analogies. In this work, we defined and formulated a logical analogy of size-change and relevant haptic cues based on observation of natural interaction. We therefore did not explore alternate ways to interpret the haptic cues and different mental reference points that support the interpretations. Although during pilot studies, it was clearly apparent that mapping the reverse finger-positioning sequences to the current analogy was perceived as strange, future works investigating different interpretation of haptic cues would be valuable in providing insight into repurposing the same haptic cues for multiple possible interaction contexts. For example, we were able to render opposing effects (size increase vs decrease) of a *single* object property (size) from the same set of haptic cues, but it may be possible to expand to *different* object properties (e.g. compliance, curvature, weight, etc.) with the same cues as well.

Individual/Multi-Finger Repositioning. As an initial exploration of our proposed visuo-haptic illusion approach, we explored the effect of repositioning all four fingers identically, for equal distances at equal speeds. However, we also see potential in repositioning each finger with different combinations of parameters to expand beyond expressing a uniform size-change, to also render non-uniform changes that may be interpreted as different object shapes as well. As the current finger-repositioning device is capable of repositioning each finger individually, a careful definition of finger-repositioning speed, direction, and distance parameter combinations to be examined would be the first step needed for further exploration. As with the rope application proposed, the individual/multi finger-repositioning combinations may be mapped to other haptic effects as well, such as force or object compliance.

The Use of Magnets. To ensure the fingertips are always at a known position, we used magnets taped to participant fingertips to fixate them to the device for the studies. Although the magnets are more practical than adhesives in term of strongly attaching and cleanly removing the fingertips from the device, taping them each time is less than ideal for practical usage. To minimize additional instrumentation, one possible solution may be to use concavities instead of magnets to fixate the fingertips to the device without fasteners or adhesives Figure 17. Future work to optimize the design of the rings and fingertip fixation method would be valuable in maximizing the approach's practical usability and applicability.

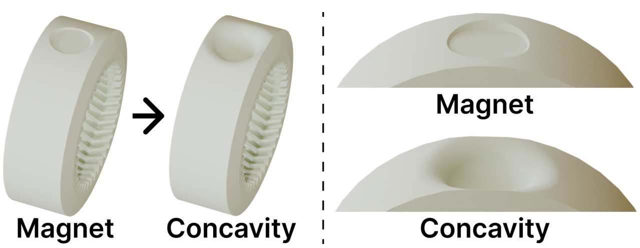

Figure 17: Alternative approach to fixating fingertips. By replacing the magnets in the ring with a concavity, the device may be capable of repositioning the fingers without additional fasteners or adhesives.

9 CONCLUSION

In this paper, we proposed a novel approach of rendering size-change perception of handheld virtual objects. Instead of changing the size of the device itself or by limiting finger motion to match that of holding a given object, we employed finger-repositioning using a hardware controller with rotating rings. We found that the specific finger-repositioning rendered by the device does not elicit a perception of size-change by itself, without a visual size-changing context mapped to the finger-repositioning motion. By providing a consonant visual context with an appropriate mental reference point, our proposed technique was seen to render a wide range of perceived size-changes within relatively short time intervals. Additionally, we were able to successfully render two opposing haptic properties (size increase vs size decrease) using the same set of haptic cues. With our proposed technique, rendering size-changes of dynamic virtual objects in various scenarios is possible. We hope this work may serve as an inspiration for future work aimed to enrich VR experiences via dynamic interactions with virtual objects.

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A TORQUE MEASUREMENT APPARATUS

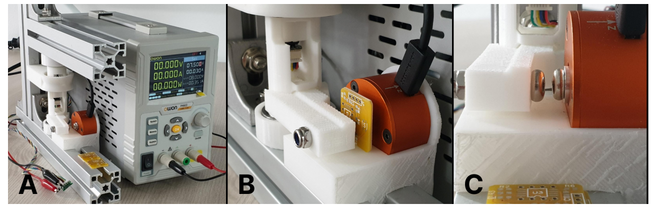

Figure 18: (A) The ring torque measurement apparatus setup with power supply. (B) Closeup of force measurement unit. The lever arm and force sensor were spaced with two PCB boards. (C) Closeup of torque measurement end effector. Round head Philips screws were fastened to both the lever arm and the force sensor to minimize contact surface area.

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