Empirically Evaluating the Effects of Perceptual Information Channels on the Size Perception of Tangibles in Near-Field Virtual Reality

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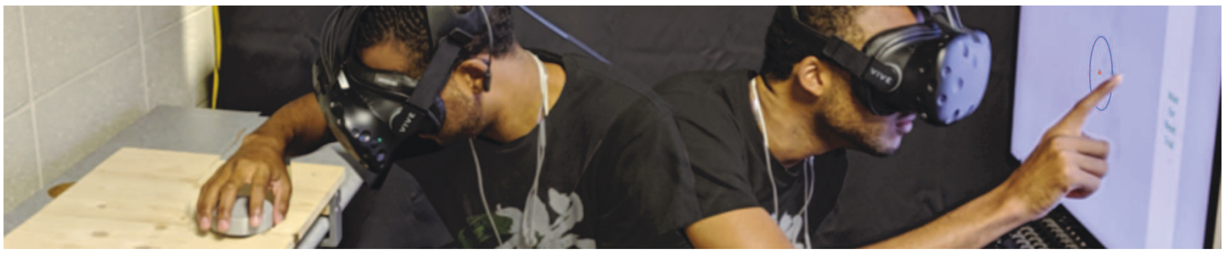

Figure 1: Participant perceives the size of a tangible dial by vision and touch while immersed in VR. To report the size, he turns to a multi-touch screen co-located with its virtual representation in the virtual environment.

Abstract

Immersive Virtual Environments (IVEs) incorporating tangibles are becoming more accessible. The success of applications combining 3D printed tangibles and VR often depends on how accurately size is perceived. Research has shown that visuo-haptic perceptual information is important in the perception of size. However, it is unclear how these sensory-perceptual channels are affected by immersive virtual environments that incorporate tangible objects. Towards understanding the effects of different sensory information channels in the near field size perception of tangibles of graspable sizes in IVEs, we conducted a between-subjects study evaluating the accuracy of size perception across three experimental conditions (Vision-only, Haptics-only, Vision and Haptics). We found that overall, participants consistently over-estimated the size of the dials regardless of the type of perceptual information that was presented. Participants in the haptics only condition overestimated diameters to a larger degree as compared to other conditions. Participants were most accurate in the vision only condition and least accurate in the haptics only condition. Our results also revealed that increased efficiency in reporting size over time was most pronounced in the visuo-haptic condition.

Index Terms: Human-centered computing—Virtual reality; Human-centered computing—Haptic devices; Computing methodologies—Perception

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1 Introduction

The rapid growth and commercialization of the Virtual Reality (VR) technology over the last few years has resulted in an exponential increase in demand for consumer-grade head-mounted displays (HMD) like the HTC Vive and the Oculus Quest. Manufacturers of these devices have hence constantly improved upon the user experience, often coming up with novel ways for users to interact with virtual worlds. Along these lines, scientists and engineers have devised enhanced methods for tracking hands, small objects, and eye gaze in VR, allowing for more immersive experiences.

An area in this fold slowly garnering more attention is the incorporation of tangible[1] entities in VR. According to the literature, the added sensorimotor experience offered by tangible objects supports an enactive mode of reasoning [9], enables empirical abstractions of sensorimotor schemes that aid learning [51], increases the sense of presence in VR [6], and tightly couples the physical perception and action spaces, paving the way for more natural immersive experiences [56]. As such, tangibles are being increasingly incorporated into VR simulations for educational and training purposes in industrial and medical settings, and their usage is expected to grow in the near future.

With the added benefits of incorporating tangible entities into VR, there is likely to be an increase in the number of applications that involve fine motor tasks wherein users are actively touching, grasping, manipulating, and perceiving tangible components. The efficacy of such simulations will often depend on how precise and accurate users are at perceiving these tangibles in terms of their basic properties like color, weight, size, texture, etc. For example, work on this front has suggested that providing texture cues on tangible objects can help dyslexic children learn to read [21], and the use of color has been proposed as a means to dynamically change the perception of size, weight, or temperature associated with tangibles [35]. In relation to size, fine motor tasks will manifest in areas such as surgery, military, and industry-related VR experiences. For example, in Hybrid Prototyping approaches [20], physical prototypes and digital models of products being developed are combined in a VR simulation. The main objective is to integrate the customer

[1] Tangible objects are physical objects of graspable size. In this manuscript, we refer to them as *tangible objects, or tangibles* for conciseness.

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in the development process and to enable a realistic experiencing of concepts in order to provide the means for design validation. Perceiving size and depth accurately is essential in this process, since skewed visuo-haptic perception could lead to design flaws in the final products. Similar challenges exist in scenarios such as VR training for surgical trainees in laparoscopic surgery [24]. These VR simulations incorporate manual tangible controls to activities that are highly dependent on the accurate perception of size and depth, such as clipping, grasping, cutting, and suturing [5]. Perceiving size and depth accurately is essential, since discrepancy in visuo-haptic perception could lead to errors and poor operative performance with the VR simulation, reducing its effectiveness. Therefore, size perception of tangibles merits further investigation due to (but not limited to) the following:

- An enhanced understanding of how the sizes of tangible entities are perceived in VR will inform us about the tolerance requirements for the fabrication of physical components.
- Many VR applications are scale sensitive (e.g. telemedicine); research in this area will inform the design of more accurate simulations that are less conducive of errors.

Several factors affect the perception of size in VR, such as the presence, appearance, and size of our self avatars [33], the distance from the subject to an object [62], amongst other aspects. These prior works have often demonstrated that different perceptual channels (and combinations thereof) can influence our perception of size. Knowledge about how participants make use of these perceptual channels to make size judgments of tangibles in VR will help us better design HMD-based VR experiences that involve the manipulation of small objects and tools requiring accurate size perception. Along these lines, early work in the real world has shown that in the presence of both visual and haptic perceptual information, the former can dominate over the latter to the point where the perceived size of small objects is more strongly dependent on what people see over what they touch [55]. There is also competing work suggesting that the addition of haptic information can reduce potential visual bias that manifests in the perception of size [26]. However, such efforts have largely focused on investigating the role of perceptual channels in the real world and desktop VR, leaving avenues open for researchers to comprehensively explore how these perceptual channels affect size perception in fully immersive VR environments with HMD viewing.

With the overarching goal of understanding what plays into the perception of the size of tangibles in near field VR, we conducted a study investigating how the visual and haptic perceptual channels affect this paradigm. In a between-subjects study, we manipulated the type of perceptual information offered in a near field size estimation task where participants were asked to either see or touch (or both) tracked cylindrical 3D printed dials, after which they reported the perceived size on a touch screen display affording a real-time, dynamic reporting mechanism in the virtual environment. Overall, this work helps further our understanding of the mechanics of near field size perception in immersive virtual environments (IVEs) featuring tangible components, contributing to this knowledge base.

2 Related Work

We perceive the environment based on sensory information provided by our perceptual channels (e.g. of vision, smell, touch, taste, etc.) [38]. The perceptual channels involving visual information and haptics information have different limitations because they obtain information by different methods [22]. Researchers have explored several factors that affect vision and haptic perception. For example, investigations have looked at how we perceive textures [25, 32, 48], weight [30], softness [30, 61], distances [17], shape [31] and sizes [39, 48, 55, 62] when vision and haptics are present, absent, or distorted in different ways. In a haptics-only experiment, Lederman and Klatzky blindfolded participants in an object recognition task [30] and found a correlation between hand movements and the type of object property being probed, such as texture, hardness, temperature, and volume.

Previous research has shown that visual and haptic modalities can both work together in a combined fashion to improve human perception of object sizes, but also against each other thereby negatively affecting the accuracy of size perception [37]. Rock and Victor [55] demonstrated in a series of experiments conducted in the real world (RW) that visual information can be dominant over haptics in experiments that included combinations of vision and haptics. According to their findings, vision can change how we perceive the haptic stimuli [55]. When presented with conflicting visuo-haptic stimuli, participants tended to report objects as "feeling the way they looked". Additionally, similar experiments also showed that participants reported the size of objects less accurately, reporting that they felt that the objects were larger when they could only touch, but not see the objects [55, 57]. There is also work that proposes that when a person looks at an object while exploring it with their hand, visuo-haptic sensory inputs are weighted optimally based on the inverse of the variance associated with the input [19]. As such, there continues to emerge work that probes into how the perceptual channels influence size perception in real and virtual contexts.

2.1 Body-based Scaling

How we perceive size depends on how we recognize the relationship between the self and the environment [42, 43, 47, 59]. Body-based scaling is the notion that apparent object sizes are perceived relative to one's body. Linkenauger et al. have shown that the hand acts as a frame of reference to scale the apparent size of objects in the environment. Put simply, estimations of virtual object size in VR differs depending on the size of one's virtual hand [33]. Hence, our body functions as a "perceptual ruler" in relation to which optical information is re-scaled [52]. When studying the near field visuo-haptic size perception of tangible objects, intrinsic characteristics of the participants' bodies such as hand and finger sizes (both real and virtual) can skew our affordance judgements along with our perception of sizes [34, 52]. In our study however, we probe into extrinsic factors that affect the perception of sizes by focusing on varying the sizes of the objects themselves. Therefore, we follow Rock and Harris' [55] protocol in which users are not allowed to see their hands while perceiving sizes. In real-life scenarios, Rock and Harris had participants perceive objects by touch only, vision only, or vision and touch while their arms and hands were covered by a black cloth. This meant that the size judgements were not influenced by participants' end effectors. In creating a similar scenario in VR, we hence did not track or render the participants' arms and hands.

2.2 Spatial and Size Perception in VR

We perceive space differently whether it is in natural environments, in photographs, cinema, or in VR [12]. We perceive our surroundings through the use of several information sources, including occlusion, height in the visual field, relative size, relative density, aerial perspective, binocular disparities, accommodation, convergence, and motion perspective. At different distances, these sources have different utility in informing our understanding of the world [12]. Hence, the space around us has been categorized into three main regions: personal space (near field), action space (medium field), and vista space (far field). These regions may slightly overlap but, in general, personal space is the area within a user's arm reach, action space is beyond personal space up to roughly 30m, and vista space is considered all further distances [13]. There are several known differences between spatial perception in RWs and IVEs. Egocentric distance – the subjectively perceived distance from the self to an object – is known to be consistently underestimated in IVEs [28],

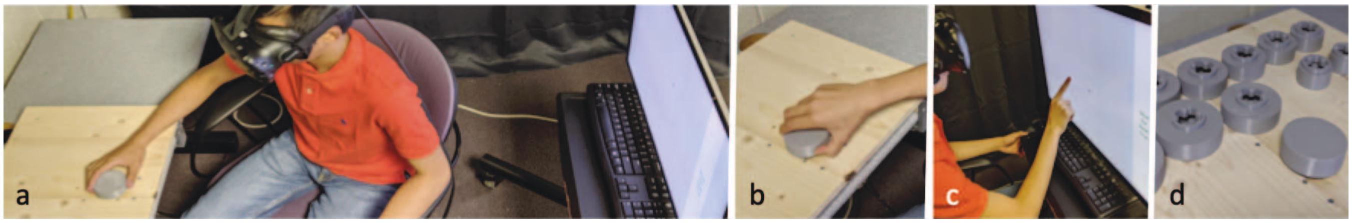

Figure 2: **General setup** *a) Participant sitting between the tracking table and reporting screen while wearing a head-mounted display. b) Detail of the participant holding one of the knobs. c) Participant reports perceived size by touch. d) Several of the 3D printed knobs.*

with the mean estimation about 74% of the modeled distances [53]. This distance estimation is influenced by several factors such as measurement methods, technical, and human factors [53]. Especially for objects at a distance (beyond an arm's length), this distortion in depth perception may also lead us to perceive an object's size as smaller, since size and depth perception are related to each other [42]. Size perception depends on depth cues combined with the retinal size of an object. To account for this, controlled studies investigating size perception in IVEs typically aim at simulating environments that are rich in perceptual cues. In our study, as we analyze the perception of size of tangibles, a number of elements surrounding participants in the RW, such as the testing apparatus, tables, computers, floors, and walls were replicated in the IVE to provide participants with rich cues, similar to what they would experience in the RW.

2.3 Perception of Size in Near-field VR

Others have explored the perception of size of objects in near-field VR. Zhou and colleagues have investigated the accuracy of depth and size perception of virtual objects in the near-field in a spherical fish tank VR display (SFTD). In comparing SFTDs with flat displays they found greater accuracy in object size perception with SFTDs [63]. In another study, the authors compared the accuracy of size perception of virtual objects displayed in screen-based displays with the size perception of real objects [58]. A grasping affordance judgement task revealed that the sizes of virtual objects were perceived as smaller than the ones in the real world. However, this difference was reduced when stereo viewing was enabled or when the virtual display was viewed before the real world. In another study also probing into virtual dials as well as buttons, and levers that the users manipulate to control a VR simulation, the authors investigated the users' ability to judge the size of an object relative to a second object of a different color [60]. They found that participants were able to perceive height and width judgements very close to the target values in virtual objects varying from 10 to 90 mm in diameter. This study differs from ours since it explored only the perception of size in relation to virtual objects. Moreover, it did not probe into aspects of the haptic perceptual channel, such as how touching, grasping, and manipulating can influence our perception of sizes.

2.4 Graspability Affordance

Others have explored how the affordance of grasping an object with one's hands (graspability) can affect perception [23,34]. Graspability has been shown to influence attention and speed of manual responses [23]. In comparing real graspable objects and matched 2D or 3D images of the items, real objects yielded slower response times overall. However, when the real objects were positioned out of reach or behind a transparent barrier, the pattern of response times was comparable with that for 2D images. The authors hypothesize that graspable objects exert a more powerful influence on attention and manual response speed than images because of the affordances they offer for manual interaction. In another study, Linkenauger et al. has examined whether the visually perceived size of objects is scaled to the extent of the apparent grasping ability for the users. In this RW experiment, the authors observed effects of graspability judgement on object size perception in which larger and smaller

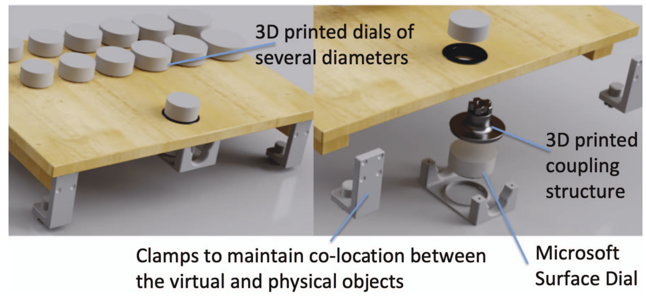

Figure 3: **Tracking table** *A Microsoft Surface Dial underneath the tracking table, augmented with 3D printed structures, allows multiple 3D printed dials to be coupled and manually switched in seconds.*

hands change graspability judgements and the accuracy of object size perception [34]. In most studies, graspability encompasses the ability to freely pick up and manipulate objects. In this study, we focus on a class of objects with practical applications, typically found in control panels and control rooms which contain for example dials, and knobs. These objects only afford rotation, and are expected to be held in a particular way. These facts, coupled with the lack or research focus on this type of controls further motivates our probe into size perception involving such objects in virtual reality.

3 Research Question and Hypothesis

There is little research on the visuo-motor perception of sizes of parametric tangible objects in interaction space in VR environments. Therefore, we wanted to explore the question how do different perceptual channels (vision-only, haptic-only, vision and haptics) affect near field size perception of tangibles in IVEs.

We hypothesized the following:

- *H1: Based on [55], tangible objects would be reported as larger when participants perceive them based on haptics only.*
- *H2: Based on [62], the addition of haptics to visual stimuli*[2] *would produce more accurate reported size estimates than with vision or haptics alone.*

4 Apparatus and Materials

Others have shown that rapid prototyping (i.e. fusion deposition modeling 3D printing, laser cutting etc.) combined with the augmentation of commercially available commodity devices (instead of high-cost special-purpose haptic devices) can provide haptic feedback

[2]We assume the baseline condition for immersive VR simulations as vision-only. Most consumer VR devices typically combine headsets, controllers, and other peripheral sensors for tracking users. Regardless, tangible interaction within VR is mostly limited to haptic feedback from tracked controllers like the Oculus Touch, HTC Vive controllers, etc, which interfere with users' ability to manipulate, or hold tangible objects naturally. The addition of natural haptic manipulation of tangibles is, therefore, an enhanced scenario. Hence, our H2 considers the *addition* of haptics to visual stimuli, and not vice-versa.

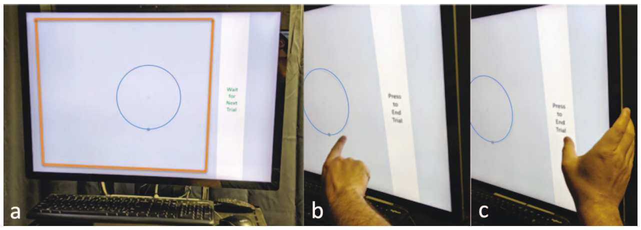

Figure 4: **Reporting Screen** *a) A Microsoft Surface Studio was employed as a multi-touch screen surface. The interface developed has two areas, the area highlighted in orange is the reporting area. To the right, we find a bar that serves both to give messages to the participant, and as a button that the participant presses to accept a reported diameter. b) Participant sliding his finger anywhere on screen to chose a diameter. c) Participant pressing the button/bar to report the size.*

within the context of tangible interfaces for VR environments [15]. Our combination of Microsoft Surface Dials, 3D printing, and the Unity 3D platform facilitates constrained parametric interactions with tangibles of graspable sizes within VR environments. Figure 2 depicts the physical apparatus developed for the experiments.

During the experiments, participants wearing a head-mounted display estimated the size (i.e. the diameter) of dials immediately after looking and/or physically interacting with them. Participants were positioned between a reporting screen – a large vertically oriented (approx. 55 inches diagonal) multi-touch screen and a tracking table – a rectangular wooden surface (14" x 20"inches) capable of tracking the rotation of removable 3D printed dials by incorporating a Microsoft Surface Dial (Figure 3).

Sixteen dials were fabricated using PLA [1], and the FDM 3D printer Original Prusa I3 MK3 [3] (eight base dial sizes with diameters of 40, 45, 50, 55, 60, 65, 70, & 75 mm, and eight with diameters increased by 10% in relation to the base set; 44, 49.5, 55, 60.5, 66, 71.5, 77, & 82.5 mm). 3D printed dials share the same height and overall appearance, and only their diameters vary. A percentage of diameter variation was chosen over a fixed amount to prevent participants from easily learning that (e.g.) the visual knob is consistently larger or smaller than the physical ones by a given fixed millimeter amount. While this method is not infallible since humans usually judge sizes using relative scales (e.g. relative to the body) [33], we tried to keep users from performing relative size inferences by, for example not rendering avatar hands, therefore reducing the number of cues available for body-based scaling and relative size judgements.

4.1 System Description

During the experiments, participants used an HTC Vive head-mounted display. The resolution of the HMD is 1080 x 1200 pixels per eye (2160 x 1200 pixels combined) for viewing the stereoscopic virtual environment. The field of view of the HMD is 100 horizontal degrees and 110 vertical degrees. The virtual environments were calibrated to render a carefully registered virtual model of the physical environment. Fusion 360 and Maya were used to create an accurate virtual replica of the environment, reproducing the physical room and apparatus in terms of size, scale, and appearance.

A Microsoft Surface Studio machine was used to implement the reporting screen (Figure 4). The VR simulation was created with the Unity 3D engine. A desktop machine (Intel Xeon W-2123 CPU, 64 GB of RAM and an NVIDIA GeForce RTX 2080 graphics card) runs the VR simulation and communicates with the tracking table and the reporting screen. Communication was achieved by Open Sound Control (OSC) messages. OSC is a low-latency protocol for exchanging messages among computers, sound synthesizers, and other multimedia devices [4]. The low-latency characteristic of OSC meant that users instantaneously saw in VR the circle they were drawing on the reporting screen. OSC messages also communicated the rotations of the Microsoft Surface Dials to the VR host machine. Figure 6 shows details of the architecture developed.

Figure 5: **Virtual models developed for the study** *a) Virtual experimental room replicating the real environment. b) Reporting screen replicating a Microsoft Surface Studio machine. c) Tracking table, d) Researcher GUI.*

4.2 Selecting Dial Sizes

Several studies postulate that the adult male maximum grasp size is around 50-60 mm, while the adult female maximum grasp size is around 45-55 mm [11, 49]. The maximum grip span however may be defined differently since individuals have different hand sizes [41]. We made sure to have both male and female typical grasp sizes present in our selection of dial sizes, and defined a selection of sizes that included some larger and some smaller diameters. In a study classifying dial sizes [41], a 5 mm variation in diameter was used to define small, medium, and large optimal diameters for dials according to their shapes. These sizes varied from 25 mm to 80 mm in diameter in 5 mm increments prompting our selection of sizes. To reduce the number of possible dial combinations and trials, we excluded dials of diameters less than 40 mm, keeping the ones that produced larger differences between the base and the enlarged set.

4.3 Selecting the Reporting Strategy

A number of reporting strategies have been employed regarding reporting the size of objects, such as verbal reporting [33], physically scaling a virtual object in VR [29], visually matching objects by pointing or drawing in the RE [55] and matching a virtual on-screen image with a physical object [34]. Prior research has underscored the superiority of manual responses over verbal reports [45, 46]. Hence, perceived sizes were reported by interacting with a physical multi-touch screen, co-located and synchronized with a simulated replica in VR. After participants look at and/or haptically manipulate the horizontal stimulus dials they turn 180 degrees and report the perceived size by sliding a single fingertip on the vertical screen to alter the size of a circle. This keeps participants from holding the posture of their hands after grasping the dials to report the size in the haptic conditions, thus preventing them from utilizing any form of muscle memory that could influence their reports. A similar strategy was previously adopted in a study in which users drew a square on a piece of paper after perceiving objects in conditions similar to our research (with vision, and/or haptic stimuli) [54]. While tracking hands and fingers to use as a reporting strategy was technically a possibility, we wanted to avoid the influence of the avatar's hands as a body-based scale.

4.4 Registration of the Virtual Environment

To verify the one-to-one mapping of the virtual environment onto the physical space, we adopted the method described by Bhargava et al. [8]. This 2-step process involves tactile feedback from the HTC

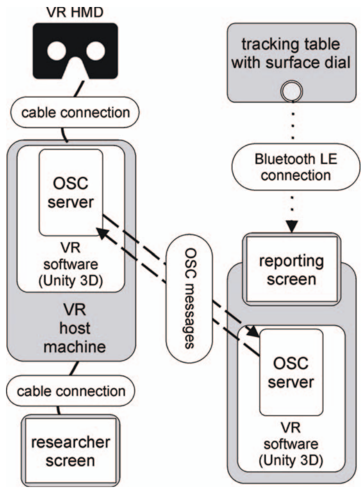

Figure 6: **System Architecture: tracking table, reporting screen, and VR host machine** *The Microsoft Surface Dial on the tracking table is connected via Bluetooth LE to the Microsoft Surface Studio Machine running the reporting screen. This machine exchanges OSC messages with the VR host machine, which runs the main VR simulation and is connected to the wired VR HMD.*

Vive controllers, tracker recordings, and the visual angle subtended in the HMD in use. For the first step, we touched the tracking table at multiple locations with the controller and checked for tactile feedback. If a tactile feedback was received, we checked if the front tip of the left corner of the virtual tracking table overlapped with the exact location on the real tracking table. In case the location was off, an offset was calculated based on the controller's position and the tracking tables' position. This offset was applied to the tracking space in Unity. The second step involved verifying the visual angle subtended. We visually aligned the HTC Vive controller to an edge of the tracking table in the virtual world first and then took off the HMD to see if the real controller visually aligned with the same edge of the real tracking table. This validated not just position but also scale of that object. This process was repeated for all horizontal and vertical edges of the tracking table and also for the reporting screen from different viewing distances. This was possible since the reporting screen was aligned and fixated in place in the real world in relation to the tracking table (facing the tracking table at a 90° angle and at a 1 meter distance). We also used this process to validate the scale and collocation of dials in the tracking table.

5 Study Design

To empirically evaluate how the different perceptual information channels affect the perception of size of tangibles in near field immersive virtual experiences, we conducted a between-subjects study manipulating the type of perceptual information offered across three experimental conditions; 1) Haptics only condition, 2) Vision only condition, and 3) Vision+Haptics condition.

In the Haptics only condition, participants were allowed to only touch the tangible dials and had to report on their size estimates based solely on haptic perceptual information. In the vision only condition, participants were allowed to only look at the dials and had to report their size estimates based solely on visual perceptual information. In the Vision+Haptics condition, participants could both see and touch the dials after which they reported size estimates based on both visual and haptic perceptual information. All participants performed the task described in Section 5.1.

5.1 Tasks

In this study, participants were required to perform a size estimation task over multiple trials featuring dials of different diameters. Participants estimated the diameter of all 16 dials three times, totaling 48 trials. The order of the trials was randomized. In each trial, participants were allowed to perceive the dial using the perceptual information offered in the experimental condition they were assigned to. Following this, they had to report their diameter estimates on a touch screen display described in Section 4.1. This meant that a participant assigned to the Vision only condition was allowed to only look at the dials, after which they provided their diameter estimates on the reporting screen. Similarly, participants in the Haptics only and Vision+Haptics conditions were allowed to perceive the dials only by touching them or both touching and seeing the dials respectively. Participants were asked to report their estimates as soon as they felt they were ready to make the diameter judgements to ensure that minimal delay between perception and reporting. It took each participant on average 45 minutes to complete the experiment.

5.2 Participants

A total of 30 participants were recruited for this Institutional Review Board (IRB) approved study, with 10 allotted per condition, from Clemson University. The average age of participants was 24 years (std dev = 4.78) and 44% of the them were males. All participants had normal or corrected-to-normal vision. A total of 24 participants reported having less than five hours of VR experience and six participants reported that they had over five hours of VR Experience. Overall, VR Experience did not significantly differ across conditions.

5.3 Procedure

Participants were greeted and asked to read and sign a consent form upon arrival. They were verbally reminded that they could quit at any time. After consenting to participate in the study, participants filled out a questionnaire that included questions about VR experience and general demographics. The participants were then randomly assigned to one of the three experimental conditions. Next, we describe the procedural sequence for participants in the conditions.

1. After filling out the pretest surveys, participants were asked to sit between the tracking table and the reporting screen (see Figure 2). The instructions did not mention anything about the purpose of the experiment to avoid priming participants.

2. The interpupillary distance (IPD) of the participant's eyes were measured with an Android smartphone app called PD Meter [2]. In this process, a picture of the subject's face is taken, and the IPD is calculated by the app. The researcher would then use this information to adjust the IPD in the HMD accordingly.

3. Participants then wore the HMD, taking some time to familiarize themselves with the environment. In doing this, they were asked to look at and touch both the tracking table and the reporting screen. The researchers then instructed participants on how to report size estimates using the screen, as well as how to follow the instructions on screen to successfully complete each trial. Following this, participants began performing the trials, following the instructions displayed on the screen.

4. At the start of each trial, participants would face the reporting screen, displaying the message "Wait to begin next trial". Meanwhile, the researcher would place the appropriate dial on the tracking table and press a button informing participants (through message on reporting screen) to turn towards the tracking table and begin the trial. Participants were instructed to take as long as they desired examining the dial before reporting the estimated size. Participants perceived the dials using the perceptual information available in the experimental condition they were assigned to. Most participants took anywhere between 5 and 10 seconds. In conditions involving haptics,

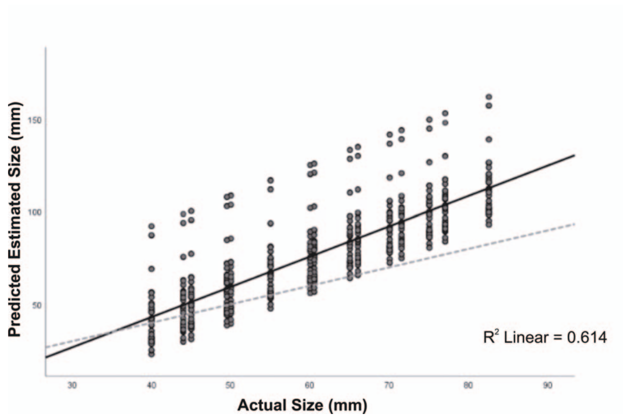

Figure 7: Estimated Dial Sizes for each presented Dial Size. The grey dotted line reflects the actual values of dial size.

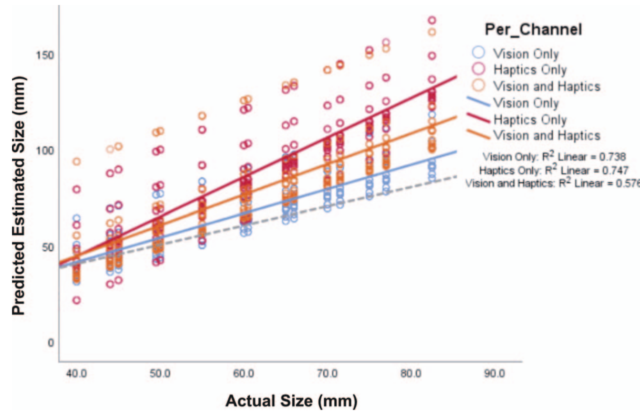

Figure 8: Interaction between presented dial size and perceptual channel. The grey dotted line reflects the actual values of dial size.

participants were requested to rotate the dials at least a few degrees reproducing actions typically involving haptics with dials. After participants felt that they had sufficiently perceived the dial, they rotated their chairs toward the reporting screen, providing estimates of size immediately after turning. By having participants rotate their chairs by 180 degrees, we ensured that the dial was outside the participants' field of view, preventing them from going back and forth between the dial and the reporting screen while reporting their perceived sizes. This marked the end of the trial. Trials featured dials of different sizes, and the order of the trials were randomized.

5. After completing all trials, participants removed the HMD and were debriefed. This marked the end of the study after which they were financially compensated for their participation.

5.4 Analysis Preparation

Normality. To meet the assumptions for linear regression, the dependent variables were plotted and tested for normality. It was found that perceived size was normally distributed and did not require transformation.

Outlier Analysis. For each analysis, residuals were obtained from the full model, and then standardized. The standardized residuals were plotted and then inspected for overly influential cases that fell outside of a normal distribution [10]. Selected outliers were removed from the dataset. In each of the analyses, it was found that <1% of the trials were removed due to outliers.

Hierarchical Linear Modeling. Due to the repeated measures design of this experiment, variables had considerable nesting within participants. That is, since each participant completed multiple trials, a portion of the variance in their responses can be attributed to a common source - the fact that the same participant was responding to each trial. This, along with other manipulated within-participant factors, created multiple levels of variance.

In a mixed model regression, Level 1 (within-participant) variables represent those that change from trial to trial, producing residual variance from the regression line. Level 2 (between-participant) variables represent those that change from participant to participant, producing variance in the intercept of the regression equation. Level 1 by Level 2 interactions occur when within-participant effects are moderated by between-participant variables, producing variance in the slope of the regression equation. In order to account for variance at the within-participant and between-participant levels, hierarchical linear modeling was used [27].

When using hierarchical linear modeling, it is important to hold the regression coefficient of the intercept constant across all models. In order to do this, continuous variables were grand-mean centered. Thus, the intercept coefficient of the regression equation represents the predicted outcome of the first trial when all continuous variables are held at their average.

Effect sizes for each fixed effect will be presented as the change in R^2 (proportion of explained variance) comparing the model that includes the fixed effect and that same model with the fixed effect removed. The resulting sr^2 can be interpreted as the percentage of variance accounted for by the fixed effect. Level 1 variables account for residual variance, Level 2 variables account for intercept variance, and Level 1 by Level 2 interactions account for slope variance.

For the following regression models, effects of continuous predictors are indicated by the regression coefficient (B), and effects of categorical variables are indicated by the omnibus F test.

Table 1: Omnibus F test results for the hierarchical linear model predicting estimated dial size

Predictor	df1	df2	F	sr^2
Level 1 (residual variance)				
Trial	1	1385.98	0.107	–
Dial Size	1	1385.98	4285.31***	.75
Level 2 (intercept variance)				
Perceptual Channel	2	26.96	3.99*	.18
L1*L2 (slope variance)				
Percept. Channel * Trial	2	1383.98	1.56	–
Percept. Channel * Dial Size	2	1383.98	100.69***	.36

Note: * indicates $p<0.05$, ** indicates $p<0.01$, *** indicates $p<0.001$

5.5 Results

5.5.1 Estimated Dial Size.

See Table 1 for the results of the omnibus F test predicting estimated dial size and Table 2 for the regression coefficients for continuous predictors. The regression model was computed holding presented dial size at its average (60 mm). The overall intercept of our model, 76.98, indicates that participants tended to overestimate dial sizes. This is further indicated by the significant main effect of presented

Table 2: Regression coefficients for continuous predictors.

Predictor	B (SE)	df	t
Intercept	76.98 (4.87)	27.62	15.82***
Trial	0.007 (0.02)	1385.98	0.328
Dial Size	1.64 (0.25)	1385.98	65.46***

Note:*** indicates $p<0.001$

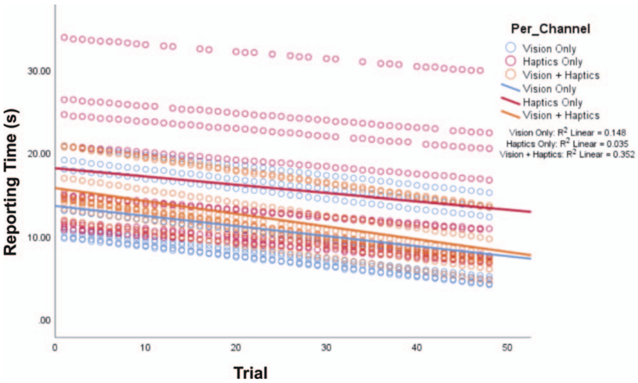

Figure 9: Interaction between Trial and Perceptual Channel in the model predicting Reporting Time.

Dial Size, where every 1 mm increase in presented dial size corresponded to a 1.64 mm increase in estimated dial size. This predictor accounted for 75% of the residual variance. Additionally, there was a statistically significant main effect of Perceptual Channel. On average, the intercept of the Haptics Only condition was significantly higher (*intercept* = 85.87, *SE* = 6.8) than the Vision+Haptics condition (*intercept* = 76.98, *SE* = 4.87) and the Vision Only condition (*intercept* = 66.56, *SE* = 6.8). These results suggest that there is increased overestimation in the Haptics Only condition compared to both the Vision+Haptics condition and Vision Only condition (see Figure 7). This effect accounted for 18% of the intercept variance.

The effect of Perceptual Channel significantly moderated the effect of presented Dial Size, such that the slope coefficient for presented Dial Size was significantly steeper in the Haptics Only condition (B = 2.06, *SE* = 0.06) than in the Vision+Haptics condition (B = 1.6, *SE* = 0.04, p $<$.001), and in the Vision Only Condition (B = 1.27, *SE* = 0.04, p $<$.001). Further, the slope coefficient for presented Dial Size was significantly steeper in the Vision+Haptics condition compared to the Vision Only condition (p $<$.001, see Figure 8). This interaction accounted for 36% of the slope variance.

5.5.2 Reporting Time

After examining a dial, participants were asked to rotate their chairs 180 degrees toward the reporting screen to report on their perceived size. The reporting time was measured from the moment the tracking table disappeared the participant's field of view until the moment they pressed a button on the reporting screen to enter their perceived dial size. See Table 3 for the results of the omnibus F test predicting Reporting Time(s) and Table 4 for the regression coefficients for continuous predictors. The regression model was computed holding presented dial size at its average (60 mm). There was a statistically significant main effect of Trial. On average, estimated reporting time decreased by 0.12 seconds from each Trial to the next. That is, participants made faster responses as they progressed through the experiment. This effect accounted for 9% of the residual variance.

Further, the effect of Trial was moderated by Perceptual Channel, such that the slope coefficient for the Vision+Haptics condition was significantly steeper (B = -0.15, *SE* = 0.02) than the Haptics Only condition (B = -0.08, *SE* = 0.03, p = .01). The slope coefficient for the Vision Only condition (B = -.12, *SE* = 0.03) was not significantly different from the Haptics Only nor Vision+Haptics conditions. This interaction accounted for a trivial amount of the slope variance.

Lastly, while the main effects of Perceptual Channel and presented Dial Size were not statistically significant, the interaction between the two variables was significant. That is, the effect of Perceptual Channel on Reporting Time depended on presented Dial Size. The slope coefficient for the Vision+Haptics condition was significantly shallower (B = -0.04, *SE* = 0.02) than the Vision Only condition (B = 0.05, *SE* = 0.03, p = .001). The slope coefficient for the Haptics Only condition (B = -0.0002, *SE* = 0.03) was not significantly different from the Vision Only nor Vision+Haptics conditions. This interaction accounted for 24% of the slope variance.

Table 3: Omnibus F test results for the hierarchical linear model predicting reporting time

Predictor	df1	df2	F	sr^2
Level 1 (residual variance)				
Trial	1	1366.93	129.29***	0.09
Dial Size	1	1366.91	0.04	–
Level 2 (intercept variance)				
Perceptual Channel	2	26.88	2.44	–
L1*L2 (slope variance)				
Percept. Channel * Trial	2	1364.93	3.33*	0.001
Percept. Channel * Dial Size	2	1365.91	5.33**	0.24

Note: * indicates p$<$0.05, ** indicates p$<$0.01, *** indicates p$<$0.001

5.6 Discussion

The statistical analyses revealed that participants consistently overestimated the size of the dials regardless of the type of perceptual information that was presented (see Figure 7). It is important to note that while the study consisted of only 10 participants per condition, totalling 30 participants, we had a considerable number of trials per participant (48 trials). This being said, we observed that participants in the Haptics only condition overestimated sizes to a larger degree than participants in the other conditions. This is in line with real-world work conducted by Smith et al. who showed that sighted individuals exhibit marked overestimation when asked to estimate the sizes of objects in the presence of haptic perceptual information alone [57]. Participants were most accurate in estimating size when presented with only visual perceptual information and were least accurate when they had to rely solely on haptic perceptual information in their judgments of size (see Figure 8). This is in line with results from Pettypiece et al. that showed that greatest uncertainty was observed with haptic information alone when compared to visual information or visual and haptics in manual estimations of the size of objects in a real world experiment [50].

These results seem to suggest the existence of an influence of users' familiarity in size perception metaphors on accuracy. Since perceiving size by only touching an object reflects a scenario that is relatively atypical (for participants with normal eye sight), participants may have scored low on accuracy simply because of their unfamiliarity in perceiving size that way. Along these lines, visual information being present reflects a perception metaphor that users are possibly more accustomed to, thereby explaining our observation of higher accuracy in the conditions featuring the presence of visual perceptual information. This has been discussed by works such as Smith et al., who showed that sighted people are less accurate than blind individuals in size estimation when perceiving objects with only haptic perceptual information [57]. Since blind people are more accustomed to perceiving objects by manual touch, their superior performance in size estimation reflects the importance of the familiarity in the perception metaphor in size perception.

However, we observed that when presented with both visual and haptic perceptual information, participants were less accurate in estimating size than when they were presented with visual information alone. This counters the reasonable expectation of more diverse perceptual information channels resulting in higher accuracy in size estimation, such as proposed by Ernst and Banks [19]. Ernst and

Table 4: Regression coefficients for continuous predictors

Predictor	B (SE)	df	t
Intercept	14.85 (1.79)	27.94	8.27***
Trial	-0.12 (0.01)	1366.93	-11.37***
Dial Size	0.002 (0.01)	1366.91	0.2

Note:*** indicates p$<$0.001

Banks suggest that humans integrate visual and haptic information in a statistically optimal fashion. Our results seem to point towards a conflict between the two perceptual channels as a reason for our observations. This has been discussed by [37], who demonstrated in a real-world setting that visual and haptic modalities can both work together to improve human perception of object sizes as well as compete against each other, thereby worsening size perception. It may hence be the case that some visuo-haptic perceptual conflict is created as a result of impoverished fidelity in seamlessly integrating tangible components into VR simulations and that this conflict results in lower accuracy in size estimation. More work is needed to thoroughly investigate the influence of this perceptual conflict on size estimation in VR. Alternatively, it may be that participants in the visuo-haptic condition explored the tangibles in a manner that was potentially unfamiliar to them based on real-world experiences, without visual information of their end effectors reaching and grabbing the object under examination. Prior research in VR has shown that end effector representations can influence the perception of size of virtual objects that one is interacting with [36, 44]. It may hence be that in the visuo-haptic condition, due to the lack of intrinsic visual information of the participants' virtual hand, this condition may not have afforded effective size perception of the tangible. This is one of the interesting aspects of our results that we hope to examine in future work. It is important to note that we made a conscious decision to avoid providing participants with their end effector representations as we wanted to examine the influence of extrinsic visual and haptic channels on size perception, without giving participants a relative scales that they could use in the tasks.

With regards to the reporting times analyses, a learning effect was observed wherein the time taken to report size estimates reduced over the course of the experiment with later trials taking less time (See Figure 9). This increased efficiency in reporting time was more pronounced in the Vision+Haptics condition. The discrepancy in the perceptual channels involved in the perception phase and reporting phase can help explain these results. When perceiving sizes, the perceptual channels involved in this study changed across experimental conditions involving Vision, Haptics, or both. The reporting, however, aimed at leveraging both the visual and haptic perceptual channels where participants had to look at the reporting screen and haptically adjust the size of a circular widget (represented on the screen) by sliding their finger on it. A faster decrease in the reporting time in the Vision+Haptics condition can hence potentially be explained as a consequence of the alignment of the perceptual channels involved in the reporting mechanism and the perception metaphor. Along these lines, having to translate from a vision only or a haptics only perception to a Vision+Haptics based reporting mechanism could be why we observed a slower increase in reporting efficiency in the two conditions involving only one perceptual channel.

Overall this study demonstrates that participants consistently overestimate the size of tangible components regardless of the perceptual channel they use in making size judgments. Furthermore, the degree of habituation one has developed in perceiving size through the perceptual channels seems to affect their accuracy in this near field size estimation task. In other words, users seem to be more accurate in estimating the size of these tangibles when they perceive it in ways they are most familiar with. This study also served to highlight the potential for perceptual conflicts that may arise when both visual and haptic information is provided in VR simulations in an effort to create more immersive experiences by integrating tangible components. These perceptual conflicts can result in lower size estimation accuracy, unpleasant breaks in immersion, and incorrect affordance judgments in the case of training simulations.

6 Conclusion and Future Work

Immersive virtual environments that incorporate tangible physical objects are becoming more popular for training in industries like healthcare, military, and manufacturing. This makes it important for researchers to understand how to improve the efficacy and effectiveness of such simulations. There is little research on the visuo-motor perception of size of parametric tangible objects in personal space interactions in VR environments. Our work investigates how different perceptual input channels (vision-only, haptic-only, vision plus haptics) affect size perception of tangibles in IVEs. The result of the proposed work is an empirical evaluation of input channels on size perception of tangibles of graspable sizes in interaction space in VR.

In a between-subjects design, participants reproduced the size (diameter) of a tangible dial after receiving haptic information, visual information, or both. That is, they reproduced perceived dial size after grasping and turning the dials without vision, after looking at a dial without grasping it, or after both grasping and looking at the dial. In the experiment, 16 different dial sizes were employed within each condition. At the end of each trial the participants reported on the perceived dial sizes. Results revealed that overall participants consistently over-estimated the size of the dials regardless of the type of perceptual information that was presented. Participants in the Haptics only condition overestimated diameters to a larger degree as compared to other conditions. Participants were most accurate in the vision only condition, and least accurate in the haptics only condition. With respect to the analysis on reporting times, overall the time taken to report size estimates reduced over the course of the experiment, with later trials taking less time, suggesting that a learning effect took place. This increased efficiency in reporting size over time was more pronounced in the Vision+Haptics condition. Overall, this work contributes to the much needed body of knowledge on near field size perception literature in VR featuring tangible objects of graspable sizes integrated into IVEs.

A limitation of our work is that we did not provide participants with a form of virtual hand representation in VR. Although it is currently not feasible to generate scaled hands for users in VR with off-the-shelf devices, prior work has demonstrated that end effector representation can influence the perception of size of virtual objects [36, 44]. As a next step, we plan to incorporate scaled virtual hands into our simulation and investigate how that affects size perception of tangibles with different perceptual channels. Previous research in a real environment has also shown that wielding an object, as opposed to just touching it, can lead to more accurate estimates of size [40]. Therefore, we intend to extend this research to incorporate graspable tangibles that can be held in hand and freely manipulated by users. Others have also investigated how vision can be used to alter the perception of the shape of tangibles in virtual environments [7, 16]. Further work investigating how vision and haptics can alter how we perceive other characteristics of tangible objects in VR can also be pursued. Findings from such efforts can further inform us on how to maximize accuracy in object size perception when designing VR experiences with tangibles that afford free wielding interactions. Research in VR has also shown that users can learn to better estimate distance, size and depth in VR with calibration [14, 18]. Therefore, another fruitful extension of our work could be understanding how calibration affects the size perception of tangibles in VR for different perceptual channels of information.

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