# A STUDY ON EFFECTIVE REUSE OF A PHYSICAL PROP USING PASSIVE AND ACTIVE HAPTICS IN VIRTUAL REALITY

A Thesis

by

MOHAMED SUHAIL MOHAMED YOUSUF SAIT

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| Chair of Committee, | Eric D. Ragan |
| Committee Members, | Francis Quek |
| | Bruce Gooch |
| Head of Department, | Tim McLaughlin |

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ABSTRACT

In virtual environments, the user cannot touch or feel the virtual objects. A straightforward way to solve this problem is to set up motion-tracked real objects that represent the virtual objects. An ideal proxy object must match a virtual object in position, geometry, surface texture, motion and weight. However, creating such a physical setup on a large scale can be a challenging task due to limited physical tracking spaces and the cost involved in building the infrastructure. Hence, the reuse of the physical prop or surface is essential. Our research focuses on studying the efficient reuse of a physical prop to map multiple virtual objects, interactions, and object properties. An *interaction-based hand redirection* technique was developed and implemented in a VR puzzle game/study to understand general usability and user preference, in comparison with a non-haptic case. In the study, there were cases where the position of the passive haptic object was moving outside the user's comfortable area of reach, making it harder to re-apply the hand redirection technique, without resetting the position of the physical prop. One possible solution was to scale virtual object motion to eliminate the problem of resetting, but the amount of scaling needed varied for different interaction types. Hence, a second user study was conducted to investigate the human perception of scaled virtual interactions in object manipulation tasks. Results from the work reported in the thesis showed that it could be difficult to detect a moderate amount of scaling, and this outcome is favorable in varying the mapping between the real and virtual worlds. To further learn the reuse and role of props in representing other object properties such as weight, we built a light-weight *vibrotactile haptic system* and tested its influence on the perception of the weight of real objects by conducting a user study. Outcomes from this study showed a trend of lower frequency actuation making a real object feel heavier than its actual weight when a vibrotactile feedback was applied on the user's forearm. This result adds to the potential reuse of the same prop to represent multiple virtual objects which could differ in object weight.

# DEDICATION

To Allah SWT, family, friends and other loved ones.

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# 1. INTRODUCTION

## 1.1 Motivation

Primary user interactions in virtual reality (VR) include travel, navigation, selection, and manipulation of objects in the virtual environment. As one of the effective object manipulation methods, prior research works have used motion-tracked props as proxies for virtual objects to interact with the virtual world. With the use of props, researchers have also observed higher interaction fidelity and better task performance in comparison to controlling a virtual object with a game controller. Motion-tracked props used in these experiments closely match to the mapped virtual object in size, shape, texture, and weight. However, in reality, creating a replica of a large virtual space with one-to-one mapped physical props is an impossible task considering the limited tracking resources, high implementation costs and dynamic nature of the virtual world. Due to these limitations, reuse of existing props and surfaces to match to multiple virtual objects is one of the viable solutions. Being said that, reuse of props need newer object interaction techniques, mechanisms and better understanding of human perception of motion, size, and weight. In our research, we developed interaction techniques that help in enhancing user experiences in case of using a single passive haptic prop. Moreover, we optimized the techniques with better understanding of human perception of object motion and weight using both passive and active haptics.

Ideally, a user would be able to interact with the virtual world by direct physical hand manipulation. One simple and effective alternative is to use *passive haptics*, which involves the use of low-fidelity physical props that resemble the virtual objects [1]. In that case, use of passive haptic objects significantly enhanced the user experience by providing a sense of touch to virtual objects. Along with the merits of using passive haptics in virtual environments, comes the challenges of reusing the physical props. For an ideal experience, use of physical props need to align with the virtual objects in shape, size, texture, and weight. And creating a dynamic prop which could change its form, and composition can be challenging to construct. Researchers in the past have come up with both passive and active mechanisms to simulate shape [2], texture [3], and weight of the virtual objects [4, 5, 6, 7]. Though these mechanisms have been fairly successful in addressing one or two properties of a virtual object, their complex setup and implementation costs make it harder to address the solution for a wider audience. Our research focuses in a mixed haptic approach, tapping the advantage of tactile sense from a passive haptic prop and using a lightweight wireless haptic system to help influence the perception of weight of the physical prop used.

Additionally, with the advancements in home entertainment VR systems, tracking a physical object with a motion-tracked controller or pucks have become easier to set up. And Current VR gamers are increasingly using props to play their games. However, use of motion-tracked props can be a fun experience, sooner the state of a unchanged prop leads to dissatisfaction and more game props adding to the difficulty of motion tracking. Building dynamic props is one of the challenges for the future of virtual reality entertainment, and training applications. Our work is an study on effectively reusing a prop providing a convincing user experience in the above mentioned scenarios.

### 1.2 Objective

We aim to study methods for effective reuse of a physical prop which can dynamically map to multiple objects and at the same time transfer necessary sense of touch and object proportions. We plan to conduct user studies to understand user's preference and comfort in performing a task. We seek to address cases of interacting with tabletop objects in a seated VR experience (see Figure 5.3). By this work, we will address the following research question:

How to effectively map one freely placed physical prop to multiple virtual objects in object manipulation tasks in VR? In case of,

- Different interaction types
- Realism of virtual motion
- Perception of object proportions

To answer the above questions, we have designed, implemented and tested our techniques and mechanisms in three different experiments. Outcome and limitations of one experiment has been an essential input the next experiment.

# 2. RELATED WORK

The goal of the thesis is to explore, build and test new techniques and feedback mechanisms using passive and active haptics creating a semi-natural interaction experience for the user in virtual reality. This work combines multiple areas of research which include the use of passive haptics and perception of motion and object properties of a virtual object.

## 2.1 Role and Reuse of Passive Haptics

Many prior researchers have demonstrated the use of physical props and tangible interaction to enhance 3D interaction in virtual environments. For example, Hinckley et al. [8] used a physical plastic doll head as a proxy for rotational control of 3D models. As another example, Meehan et al. [9] had users walk on a plank of wood on the floor to provide the tactile feeling of the feet extending over the edge into a deep pit. In other work, Lok et al. [10] presented an approach for allowing virtual objects to dynamically interact with physical props by creating virtual versions of the props.

While mapping physical objects to their virtual counterparts has clear benefits for enabling realistic perception and interaction, it can be difficult to create accurate physical versions of many virtual objects. This is a major limitation for use in VR, especially since once of the key advantages to virtual environments is the ability to simulate a wide variety of scenarios and objects that may not be easily accessible in the real world. However, in his dissertation on passive haptics, Insko [1] demonstrated that physical accuracy is not always necessary for an effective result, and the combination of low-fidelity physical props with high fidelity visuals can be sufficient for increasing the sense of presence and realism. Also supporting these results is the finding that the visual sense can dominate proprioceptive senses in a situation of visual-proprioceptive mismatch [11, 12]. A similar concept has been demonstrated with *pseudo haptics*, in which visual feedback of force and motion can influence how they are perceived [13]. For example, a study by Lécuyer et al. [14] found that visual dominance can influence perception of displacement of a virtual spring squeezed by hand interaction when the given visual representation does not match the physical change, and another study demonstrated the use of pseudo haptics to simulate different surface textures [15].

As another example, Kohli et al. [16] studied the concept of *redirected touching* in a study that warped the virtual space while asking participants to touch target locations on a board in front of them. Different touch interactions with different distorted surfaces were mapped to one physical interaction board, and the researchers showed the user's virtual hand moving differently from the real hand motion to provide the tactile sensation matching the virtual world without adjusting the physical world. In other work with mismatched virtual and physical objects, Ebrahimi et al. [17] showed that visual feedback when accompanied with proprioceptive information can reinforce users' depth judgements to comfortably reach the hand to a physical target.

With a similar approach, Azmandian et al. [18] proposed a framework for enabling reaching for real-world props by warping the virtual space, virtual body and a hybrid technique that involves both. In our work, user's virtual hand position was offset in the direction of a virtual object in order to align with the physical object. When the distance between virtual and physical objects was large, shifting the virtual hand seemed noticeable by participants. Hence this research introduces warping techniques to apply translational warping to the virtual hand incrementally till the hand reaches the virtual object. Moreover, this work showed that participants were able perform significantly better in low corrective or warping scenarios.

A recent research by Han et al. [19] compared two hand redirection techniques such as *translational shift* and *interpolated reach* on the basis of effectiveness, and ability to adapt to different levels of mismatch between physical and virtual object. The outcome of this work showed *translational shift* technique to be superior in performance in comparison to the *interpolated reach* technique. Furthermore, this work outlined the significance of the direction of offset between the virtual and physical object, where the objects positioned farther from a user produced more error and increased reach times.

### 2.2 Scaling Virtual Interactions

Understanding how people perceive interactions is crucial for devising new techniques and building applications that provide convincing immersive experiences. Previous works have discussed perception of virtual distances [20], head rotations [21, 22], and physical reaching [23]. In highly relevant research on scaling for viewing, Steinicke et al. [21] presented a study on detectable thresholds for virtual distances, rotations, and curvature paths for refining redirected walking techniques. They conducted an experiment where participants tried a range of translational, rotational, and curvature gains and were instructed to classify motions as either slower or greater than the physical movement. Their research focused on deriving a range of scale factors where participants were unable to firmly detect a difference between virtual and real-world movements. As a compelling result, researchers found that users could physically turn 49 percent more or 20 percent less than the recognized virtual rotation. Moreover, by physical movement, the user's motion can be scaled up to 26 percent and scaled down to 14 percent, which remain as the boundaries of perceptible motion. Our work has similar goals and uses a similar approach, though we focus on scaled object manipulation by direct hand control.

Perception of object motion in a virtual world can differ from the real world due to the dominance of visual feedback [14, 11]. To understand these variations, Ebrahimi et al. [23] conducted an extensive study to understand the differences in perception of physical reaching in real and virtual worlds with or without visuo-haptic feedback. Their experiment tested for percentage of error, completion time, physical movement distance, average acceleration, and average velocity during a physical reach task. As outcomes of their research, they found only accurate visual feedback was able to mitigate the lack of haptic feedback for their hand reaching tasks. Moreover, there was no difference found in error rate with the presence and absence of haptic feedback, but the presence of haptic feedback significantly changed outcomes such as task time, the physical distance, and average velocity of reaching. Hence in our research, we study perception of scaled motions with direct hand interaction to understand if there is flexibility in human tolerance to discrepancies between visual and proprioceptive feedback.

Also relevant to hand interactions, Kohli et al. [24] proposed a warping technique to remap a physical surface to different virtual target surfaces at different orientations. They conducted a preliminary study with six participants to explore whether participants could classify touching actions as the “same” or “different” in comparison to one-to-one virtual-to-physical mappings. They found that users had difficulty in distinguishing discrepancies when orientation-mismatches were small, and they were confident with identifying larger offsets. This work strengthens the motivation for our own work, which includes a larger study with a variety of interaction types for 3D object manipulation, and we focus on interaction scale factor rather than surface orientations.

### 2.3 Perception of Weight

Commercially available VR systems allow object selection and manipulation through tracked motion controllers, but they do not transfer any tactile or kinesthetic information. The direct way of simulating the sense of weight is by using an actual physical prop which is an exact representation of the virtual object [25]. However, for a large virtual environment replicating every virtual object with a physical prop in the real-world is a near impossible task as previously mentioned. In the past, researchers have used mixed reality haptics systems to simulate touch senses, Borst et al. [26] developed a mixed reality system for haptic interactions on a virtual circuit board. They conducted a study combining the haptic feedback from a force-feedback glove and a physical board. As an outcome of the research, combining of both passive haptics (from the board) and active haptics (from the force-feedback glove) showed evidence in higher task performance and better subjective ratings. The use of a force-feedback glove could simulate a tactile sense of a virtual button, but a glove masks the finer tactile sensation perceived by the human touch.

In a similar line of work, Mizuno et al. [27] designed a hand-held vision-tactile-force display device capable of affecting sense of weight, using a multi-modal feedback display. In this research, they investigated simultaneously simulated interactions between vibrotactile and force perceptions. As part of the study conducted, they varied the level of vibration magnitudes on either side of the tablet and asked the participants about which side of the tablet was felt heavier comparing that to a constant stimuli case. As one of the important outcomes of this work, researchers observed weight perceptions being affected by the vibrotactile simulations based on the recorded subjective evaluation levels. Moreover, the results were notably higher in cases where the maximum force feedback was complemented by higher vibration magnitudes.

With the developments in relatively cheaper end-user tracking technologies, such as HTC Vive system, tracking physical objects with the help of a tracking puck has become easier to set up. Moreover, the importance of reusing one physical object has increased, For example the simulating a varied sense of weight of the proxy object can augment the user experience than a simple unchanged object. Addressing this problem, Zenner et al. [6] designed a Dynamic Passive Haptic Proxy (DPHP) which can shift its center of gravity to vary the sense of weight of the physical prop. In this work, they built a system with a stepper motor, a weight, a belt and pulley system to vary the center of gravity of a long rod. When the user held the haptic object at one end, with movement of the weight along the long rod, they were able to create a variation in the weight of the physical object. This difference was complemented along with visual cues by varying the scale of the virtual object in the head mounted display. Researchers measured the outcome of the experiment with user ratings for realism, exertion and fun and studied the dynamic passive haptic proxy with respect to change in length and thickness of the visually presented object. Outcome of this research showed the haptic feedback provided by DPHP was significantly more realistic and enjoyed more in comparison to an equivalent real-world object with fixed weight distribution.

Many researchers have been successful with techniques to manipulate sense of weight by changing the visual parameters like control-to-display (CD Ratio) [28] and visual diminishing the length of the object in mixed reality experiences [7]. And in our research we are set to implement a multi-modal feedback system, encompassing both visual and mixed (both active and passive) haptic feedback mechanisms to achieve change in perception of weight of the physical prop.

# 3. RESEARCH OVERVIEW

Our work sets forward to answer the research questions listed at the beginning of this document. To begin with, we designed a hand redirection technique to map a single passive haptic prop to multiple virtual objects by applying dynamic offset to the virtual hand. The first study focused on collecting user experience feedback, concerns, and limitations of using this technique in a game environment. At the end of the first study, the main limitation of reusing a prop was in cases where virtual hand appeared far from its natural position due to large distance between the virtual and physical objects, which resulted in an inconvenient user experience.

Scaling virtual object motion can help in reducing large offsets used in the hand redirection techniques. However use of higher control-to-display ratio can compromise the task performance. Therefore, a second study was targeted to understand whether participants could distinguish between different levels of scaled interactions as being different from normal one-to-one movements in direct object manipulations tasks. Knowing the detection threshold for different interaction types will help in creating user experiences with optimized comfort and control. At the end of the second study, we had improved hand redirection techniques and optimized them based on the perceptual data collected.

To address reuse of props beyond attributes such as position and interaction type, we conducted a third study to explore the effect of vibrotactile feedback on perception of weight of the real object. This study used the optimized hand redirection technique developed from the previous user studies. The outcome of this part of research will lead to possible reuse of the same physical prop to represent virtual objects which differ in both position and weight with the help of a simple augmentation of vibrotactile feedback on the user's forearm.

## 3.1 Experiment 1

This experiment is an introductory study of the reuse of a proxy object in object manipulation tasks. In this work, the participants played a VR puzzle game involving moving cylindrical puzzle pieces on a table, sliding switches, and opening doors (see Figure 4.3). One proxy object controlled all the before mentioned interaction types. When a single prop has to correspond to multiple virtual objects, it is possible that they are positioned differently in the virtual environment inside the same interaction area. To account for the positional mismatch, corresponding offset was applied to the virtual hand in such a way that it will allow the participant's real hand to reach the real-world prop correctly (see Figure 4.1).

The study followed a within-subject design, comparing two object manipulation scenarios: with passive haptics and with no passive haptics. 16 participants (9 males and 7 females) participated in the study. The data collected included feedback for usability, preferences, and frustrations from playing two versions of a VR puzzle game.

This work shows the use of a single proxy object to control different types of interactions using with different transfer functions in order to preserve high levels of interaction fidelity in each interaction. The study results found that many participants were preferred interacting with the physical prop over the pinching method without haptic feedback and the translational offset applied to the hand was vaguely noticeable. In addition, the results showed participants with preferences within different types of interactions. For example, Free movement of the puzzle objects with six degrees of freedom placed on specified targets was the favorite interaction as it was closest to the to the real world interaction. In contrast, interaction with the door was least appreciated, as participants felt a disconnect between the physical movement of the prop and the function used to swing the door open or closed.

### 3.2 Experiment 2

As one of the outcomes of experiment 1, the participants expressed an intuitive mapping between the proxy object and different types of virtual interactions such as in the object placement, door opening or lever sliding tasks. In several occasions, after each successive interaction made by the participant, the proxy object moved further away from the user and redirected the user's hand with larger offsets which became very uncomfortable for the user. One way to solve the problem of increasing hand offset introduced in the first experiment is through dynamically scaling the virtual movement of both the virtual hand and interaction. Hence in this experiment, a study was conducted to understand the different type of interactions (see Figure 5.2) by altering the control-to-display ratio (C/D ratio) which is the ratio between the amount of physical movement of a tracked physical object and the amount of the corresponding virtual movement of the object. In this work, we used a term scale factor to denote the C/D ratio (see Figure 5.1). The main aim of this experiment was to learn whether participants could distinguish between different levels of scaled interactions as different from normal or one-to-one movements. Also, we were interested in understanding the effect of scaled interactions on user's task performance or adjustment behaviors concerning different types of interactions.

The experiment followed a 12x5 repeated measures design with 12 levels of the scale factor and 5 interaction types, and we tested for two types of tasks, a quick perception task, and a free motion task. The values of the scale factor, $S$, ranged from 0.25 to 3.0 in increments of 0.25. For the selection of interaction types, our approach was to cover a variety of types of virtual movement controlled by a freely placed physical object. We selected object interactions constrained by different degrees of freedom (DOF) with either translational or rotational movement such as a horizontal slider, a vertical slider, a free moving tabletop object, a rotating dial, and a joystick. Every trial with a scale factor and interaction type had two sub-tasks. The first task was a *quick perception judgment* task, where the user was expected to move or rotate the prop to a specified virtual target location as quickly as they could. The second task consisted of a *free motion judgment* task where the participant was not constrained by time or target location but rather was encouraged to work with the presented interaction type and respond to questions that followed. Sixteen participants participated in the study including 9 males, and 7 females. The data collected comprised of participants choice of the speed of motion observed (slow, fast, or normal), confidence in percentage, time-taken for each task, and also motion capture data of every trial to infer errors and corrective behaviors.

The result of the experiment show evidence of a range of uncertainty where it is difficult to correctly classify scaling that results in motions that are faster or slower than normal one-to-one object movements. Participants were more accurate at detecting low scale factors ($S < 1$) compared to detecting higher scale factor ($S > 1$). Moreover, participants felt inconvenient to move/rotate the object in low scaling situations, which made the more prominent for detection. Also, moving the virtual object faster was appreciated as a low physical effort was needed to make large virtual movements.

### 3.3 Experiment 3

To expand the reuse of physical prop beyond position and type of interaction, we were interested to study the other virtual object properties such as object size, shape or weight. Beginning to explore object variation in weight required simple alteration to our current setup. Whereas, in cases of exploring object size and shape variations required complex build and re-design of the proxy object used in the previous experiments. As our overall goal was to create a light-weight system for reuse, we proceeded with considering object variation based on weight for this experiment.

This work is an exploratory study on the influence of vibrotactile feedback on perception of weight of the proxy object used in the object manipulation tasks. In this experiment, the user wore vibrotactile bands comprising a total of four actuation motors on their dominant arm. And as they moved the proxy object, a steady haptic actuation was felt all over their arm. The magnitude of the actuation was kept constant. Being an exploratory work, we were interested to figure out the effect of vibrotactile feedback on perceived weight based on factors such as the level of frequency of haptic actuation and its effect across range of physical object weights. The study was a discrimination task with a two-alternative forced choice paradigm. The experiment followed a repeated measures design with 3 levels of haptic actuation applied to the reference object, 3 levels of haptic actuation applied to the test object and 4 physical weights of the test objects (see Figure 6.3). The weight of the reference object was constant. Every trial had a unique combination of the conditions described above. The task was to compare the perceived weight of the two physical objects along with the haptic actuation and choose the heavier object (see Figure 6.2). The data collected included user's response for the heavier object and the time taken for making their judgment.

The experiment helped in understanding the role of topical vibrotactile feedback in conveying a sense of the weight of the virtual object. And the outcome of this study showed a trend of lower frequency actuations making the real object feel heavier than its actual physical weight. The observed effect was also carried over or felt across the range of physical weights that were considered for this experiment. Hence, the observed effect can possibly help reusing the same prop to represent multiple virtual objects which differ in weight by just altering the level of haptic actuation applied to the user’s arm.

# 4. EXPERIMENT 1*

Realistic interaction with 3D graphical environments is often one of the primary goals of virtual reality (VR). In many cases, the gold standard for object selection and manipulation would be if users could naturally use their real hands to directly interact with virtual objects while experiencing realistic haptic and tactile feedback. One straightforward and effective alternative is to use *passive haptics*, which involves the use of simple physical props that correspond to virtual objects [1]. However, practical limitations can make it difficult to arrange physical props in such a way that accurately represents the virtual world, and virtual environments are often much larger than the available tracked physical space.

To partially address this issue, researchers have explored manipulating rotations to align virtual and physical objects to allow realistic physical interaction (e.g., [29]), and perceptual illusion can be used to simulate virtual interactions that differ from the real world (e.g., [24]). Azmandian et al. [18] enabled reaching for props by warping the virtual body and virtual space so the user's virtual hand position was shifted in the direction of a virtual object, but the technique did not allow the choice of interacting with multiple objects.

## 4.1 Goals

Our research is motivated by the need for flexible techniques that allow free choice and can work in practical home-VR setups that make use of a head-mounted display (HMD). As such, we investigate accessible and viable techniques for natural haptic interaction that can work in convenient tabletop VR setups such as when a user is seated at a desk or standing in front of a table. For this reason, the research presented in this work explores methods that allow physical hand interaction with passive props while the user remains at the same physical location [30, 31]. We configured and studied the combination of Resetting and Redirected Reach, two approaches that

*Reprinted with permission from "Physical Hand Interaction for Controlling Multiple Virtual Objects in Virtual Reality" by Mohamed Suhail Mohamed Yousuf Sait, Shyam Prathish Sargunam, Dustin T. Han, Eric D. Ragan, 2018. Proceedings of the 3rd International Workshop on Interactive and Spatial Computing, 64-74, Copyright [2018] by ACM.

enable passive-haptic interaction in situations with head-coupled rendering and virtual locations. We demonstrate and evaluate our techniques in a VR game (see Figure 4.3) that uses a single physical prop to control variable types of virtual interactions with objects distributed across a large virtual environment. We conducted a controlled experiment to evaluate a method that supported passive-haptic interaction methods as compared to a virtual hand approach without haptics.

### 4.2 Interaction-based Redirected Reach

The position of the physical prop may not always in an ideal position for interaction. This is especially true when using one prop to correspond to multiple virtual objects in an environment because each object can be positioned differently within its interaction zone.

To account for mismatch, we apply translational offsets to the virtual hand in such a way that will allow the user's real hand to correctly reach the physical real-world prop. The translational offset requires the calculation of the difference in translational values of the virtual object and the physical object. The offsets are calculated upon entry to an interaction zone with an interactive object. The offset is then applied to the virtual hand, which adjusts the hand's position in virtual space. In our implementation, the virtual hand is only visible when the user enters the interaction zone, so the hand appears with the offset already applied. This way, the user does not observe any change in the hand position.

*Resetting* is a straightforward method for adjusting the orientation of the virtual environment to match the needed physical coordinate space. Numerous prior projects have demonstrated the use of resetting (e.g., [32]). We used a fade-to-black transition effect, then instantly updates the virtual world so the virtual interactive object matches the real-world prop direction, and then fades back to the virtual scene. The resetting transition triggers when the user moves near an interactive virtual object. A complete resetting transition took one second in our implementation.

After the transition, the virtual orientation has been changed so that physically turning to face the virtual object will physically align the user with the physical prop. To help users understand the resetting transition, this technique displays an arrow to denote the shortest direction of physical turning required to face the interactive object. As an additional rectification step, along with the virtual world rotation, the technique also adjusts the position of the virtual camera to be directly in front of the virtual interaction zone.

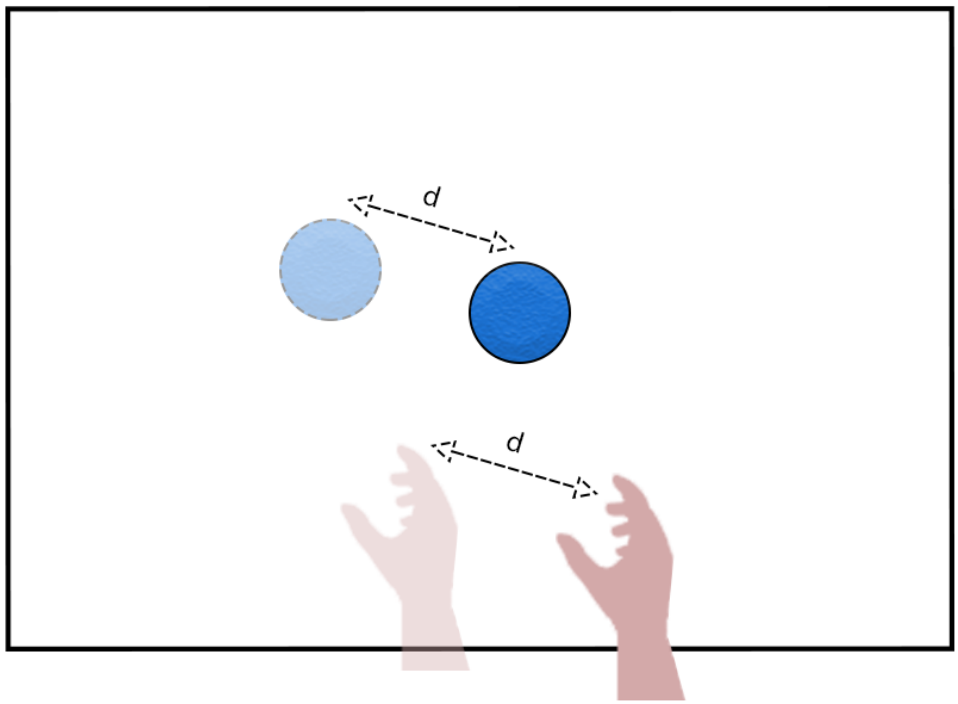


Figure 4.1: A top-down diagram demonstrating redirected reach. This shows virtual hand and the virtual object are represented by faded colors. $d$ denotes the vector offset between the virtual and physical objects [31].

### 4.3 Experimental Design

A controlled experiment was conducted to study user preference, and usability by combining passive haptics and adjusted travel techniques for seated experiences in VR. We compared the following three conditions:

- **With Passive Haptics:** This condition used one-to-one head tracking and supported interaction with the passive haptic prop with the help of resetting transitions when users virtually entered the interaction zone. Redirected reach was applied to adjust the virtual hand.

- **With No Haptics:** This condition was included as a reference technique that did not support tactile interaction using the prop. Instead, participants using pinch gestures with a tracked hand to select and manipulate virtual objects. The condition used one-to-one head tracking, and one-to-one hand tracking was used to control the virtual hand.

The experiment followed a repeated-measures design, so each participant experienced two game trials, one for each of the two conditions. Ordering for the other two versions were balanced among participants for the first and second trials.

We were interested in understanding perceptions of the different techniques and evaluating preferences for different configurations when used in a fairly realistic gameplay scenario. As such, we were more interested in subjective and qualitative results than in assessing any particular task performance metrics (e.g., speed and accuracy). We also collected relative Likert scale ratings for a variety of subjective measures such as disruption to the experience, fun, ease of use, fatigue, and comfort.

### 4.4 Game Environment

To test our techniques, we designed an immersive game environment (see Figure 4.2) that involved virtual travel and manipulation of virtual objects to solve a simple puzzle. The goal of the game is to collect five missing rocket pieces scattered across the environment. To collect the pieces, the player must complete a basic symbol-matching puzzle requiring traveling to different locations, moving objects to the correct target positions on an in-game tabletop map, and manipulating switches that toggle the availability of game objects. Once all five pieces are collected, a final switch is enabled that will complete the game once pulled.

The environment included multiple *interaction zones* at different locations that each included an interactive object. To test the feasibility of our techniques with different types of interactions, we implemented three different types of object interactions: (1) cylindrical puzzle pieces that could

Figure 4.2: A screenshot from the game environment. An interaction zone is marked with a floating red marker [31].


Figure 4.3: A screenshot showing three different types of interactions in the game. This shows (a) Moving a puzzle piece during symbol matching, (b) opening a door, and (c) operating a switch [31].

be moved, picked up, and set down, (2) large switches that slide back and forth along a fixed track, and (3) doors that swing open by moving the door handle (see Figure 4.3).

The game was designed to encourage exploration and free choice of what order to interact with different objects. Additionally, to test the flexibility of the interaction and travel methods, the environment was designed with different interaction points at different virtual orientations (see Figure 4.4). With this design, different interaction zones had different virtual orientations when

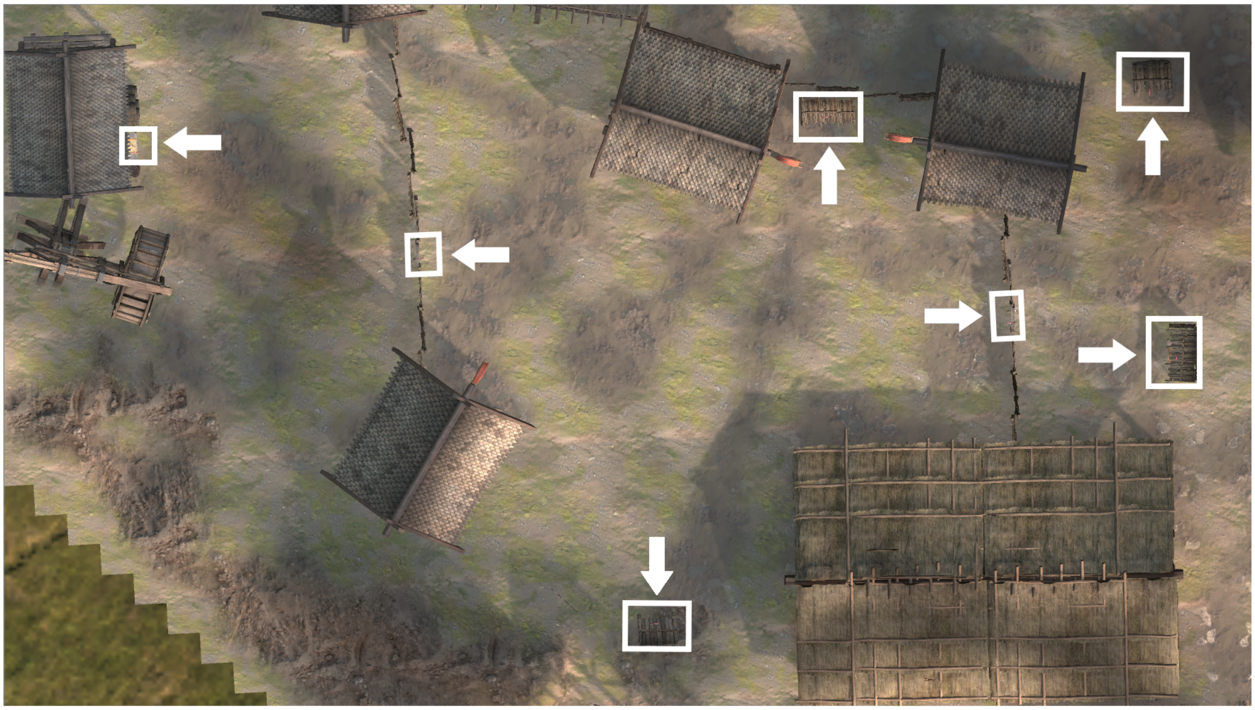

Figure 4.4: A top-down view of the game environment with interaction zones represented by white rectangles. Arrows denote the expected direction of users approaching the interaction zones [31].

compared with the physical world, so users had to physically rotate to orient themselves with the physical prop.

By default, the player does not have a virtual hand visible. When entering an interaction zone, the player's virtual hand appears to signify the ability to interact with the virtual object. To make the interaction zones easy to identify, they were labeled with a large rotating red symbol floating above them (see Figure 4.2).

## 4.5 Apparatus

The game was implemented in the Unity game engine (5.4.1) using assets from the Viking Village 3D environment from the Unity Asset Store [33]. The application was run on a computer with a NVIDIA GeForce GTX 980 GPU and a 3.6 Ghz Intel Quad Core processor. The game maintained a frame rate of $98 - 110$ frames per second.

The experiments were conducted used Oculus Rift CV1 as head mounted display. Additionally,

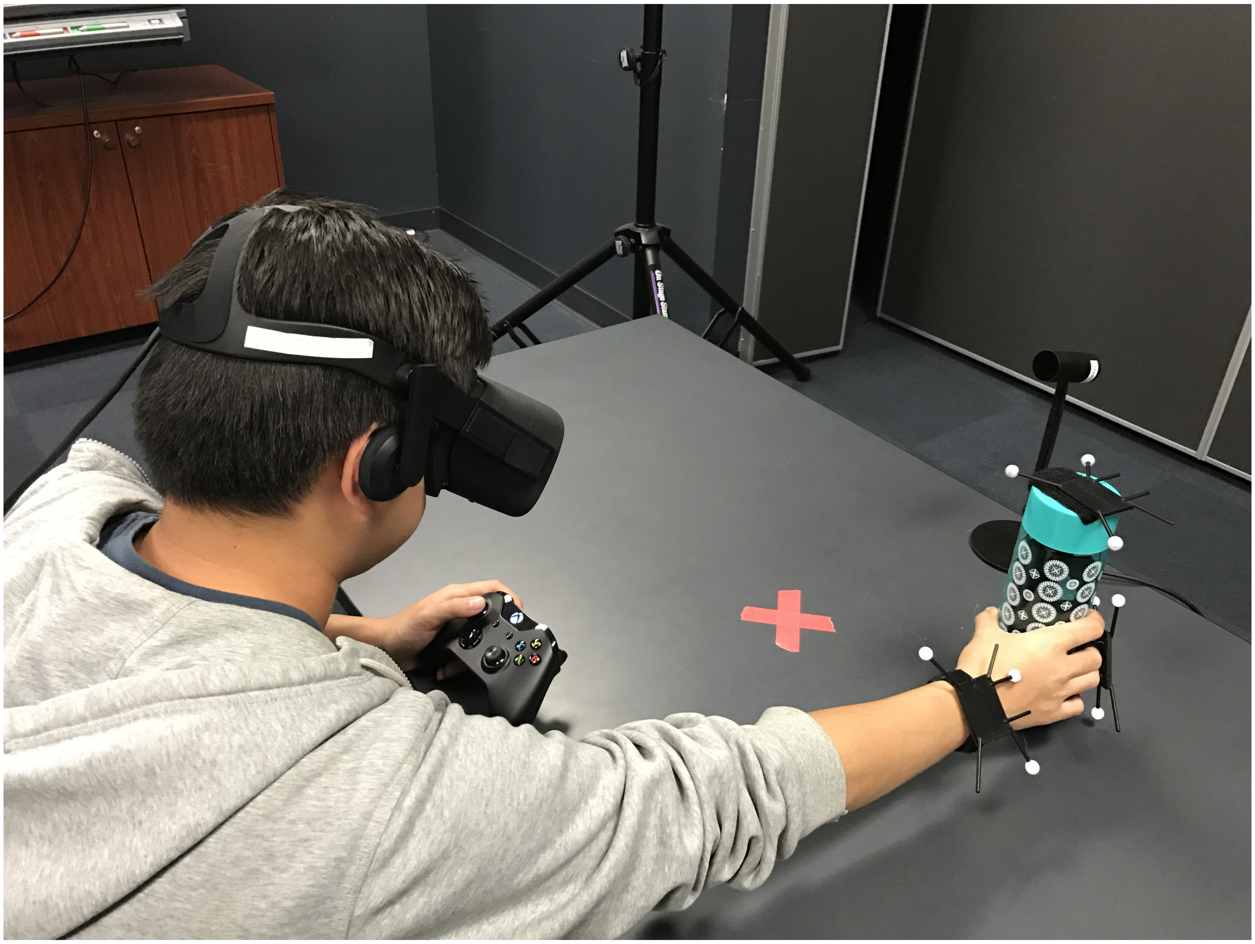

Figure 4.5: The physical setup used for the game study. Participants sat at a table and could reach and move a tracked prop (a plastic bottle). Tracking markers were placed on the wrist and fingers of the user's right hand, and the left hand was used to operate the analog stick of a game controller. Participants could rotate in a swivel chair [31].

Oculus constellation sensors were used to track head motions (both positional and rotational), though position head movements were limited because participants were seated. Participants were seated in a rotating chair facing a table and holding the interaction prop—a plastic water bottle with weights inside for added stability at the base.

To track the prop and the player's hand, the setup used an Optitrack capture system with eight Flex 13 cameras. Each of these cameras recorded tracking data at a frame rate of 120 fps operating with 8.33 ms latency (manufacturer-reported). The setup used rigid bodies for 6-DOF (degree of freedom) tracking. One of these rigid bodies was attached to the top of the prop (the bottle). The other two rigid bodies were attached to the user's right hand using custom-made velcro strips—one on the outer wrist and the other on the middle and the ring fingers. Figure 4.5 shows the physical setup with the prop and tracking markers.

A Xbox game controller was used for user input. The left analog stick controlled the virtual movement (ground-constrained translation only), and the left bumper and directional pad were used to navigate and select game-menu options (i.e., showing and hiding instructions).

### 4.6 Procedure

The entire experiment lasted 45–60 minutes, and the study was approved by our organization's Institutional Review Board (IRB). On arrival, participants were seated at a table were given an overview of the study and required to sign an informed consent form in order to participate. Participants then filled out a brief background questionnaire about demographic information (age, gender, and occupation). Before putting on the HMD and the markers on the hand, the participant was given an explanation of the controls for viewing the in-game instructions and progress bar. The explanation also provided information on how to travel in the world using the game controller and rotate in the chair.

Before starting each practice and trial session, participants were asked towards the forward direction to directly face the physical table, and the physical prop was always placed at the same starting location on the table before beginning. Before the main trials, participants were given a practice session to experience both the passive haptics and no haptics scenarios. This practice session allowed them to read through the instructions of the game as well as perform virtual interactions in the environment to get an idea of what to expect in the main trials. After the practice session, participants were required to take a short break (5 minutes).

Next, participants were asked to complete the entire game two times (one for each technique). Instructions and hints were given if the participant was having difficulty progressing in the game; since the purpose of the study was to assess experience with the techniques, we were not concerned with gameplay efficiency. On average, each trial took approximately 5 minutes to complete.

After all trials, a final experience questionnaire was given to the participant where the three versions they experienced were rated against each other in terms of fun, ease of use, preference, and overall experience. Finally, a semi-structured interview was conducted by the experimenter to collect additional feedback.

### 4.7 Participants

Sixteen participants (9 male, 7 female) took part in our study. Participants age was in between 21 and 28 with a median of 23 years. Participation was voluntary and no compensation was provided. All participants were university students in various programs, though most participants (12 of 16) were in computer science or computer engineering programs. All participants self-reported as being right-handed. Out of the 16 participants, 10 participants reported spending at least one hour every week playing 3D video games, and 11 reported some prior experience with VR before attending our study.

### 4.8 Results and Discussion

The qualitative feedback and our observations make up perhaps the most important results for understanding the tradeoffs among the techniques. The experimenter observed and took notes about participant behaviors and comments during the study, and participants answered a semi-structured interview at the end of the study. Most of the questions were directed towards a set of themes that were intended to collect information on which type of interactions felt natural, whether the hand offset was noticeable or not, and whether the resetting and guided rotation were noticeable, distracting, or disorienting. From the comments received, we undertook a thematic coding method to examine and record common sentiments and emphasize information from user experiences.

#### 4.8.1 Feedback About Redirected Reach

Regarding redirected reach, 8 of the 16 participants reported that they noticed some deviation in the position of their virtual hand from where they expected it to appear. Likewise, many participants were hesitant in reaching the physical prop initially, but they got used to the technique during the course of the study. The following quotes were illustrative of the redirected reach technique:

"I had to stretch much to reach the prop sometimes. Most of the time I wasn't able to grab the prop at the physical location I thought it would be."

"The physical prop was difficult to reach sometimes."

### 4.8.2 Feedback About Resetting

The resetting technique was applied to orient the user towards the physical prop; this technique received mixed responses from our participants. Three participants indicated that they felt this technique was clean, intuitive, and did not interrupt their game experience, while four others said the resetting at the interaction zones was disorienting. Interestingly, five participants reported that they understood that resetting was necessary to be aligned to interact with physical prop. These responses show that many participants were aware of their physical surroundings when they were supposed to interact with objects in the real world. Though not problematic, these results could suggest reduced sense of presence due to constant awareness of the real world. The following are representative comments from our study about the resetting technique:

"I didn't mind being rotated. I thought they are needed for the techniques and physical prop to work."

"I see the need for transitions to help in redirecting towards the prop."

### 4.8.3 Feedback About Multiple Interaction Types

In the game environment, participants used the prop to perform three different types of interactions: moving and placing cylindrical puzzle objects; opening doors; and sliding switches. In the post-study interview, we asked our participants to comment on the interactions. Out of 16 participants, 9 reported interaction with the door was the least favorite, and 11 participants said placing and moving the puzzle pieces on the table was the most natural and realistic type of interaction. From this data, it is clear that the most preferred interactions were those that more accurately matched the mapping to the real world movement of the physical object. Switch interaction was preferred second, as the movement of the physical prop in the real world was transformed and applied in one dimension of the virtual switch. Interaction with the door was least appreciated, as participants felt a disconnect between the physical movement of the prop and the function used to swing the door open or closed. There was also some confusion about whether to lift the physical prop or slide it on the table, indicating that the door technique was not natural and intuitive for all participants. Some of the notable responses from the participants for the different types of interactions are:

> "Opening the door was a bit tricky."

> "Placing objects was the best part. Object placement was extremely accurate."

> "The lever was nice, but no sense of weight. Sliding it on the table helped the sense of pulling."

### 4.8.4 Feedback About Tactile Interaction

Six participants indicated that the air grasping technique felt effortless and intuitive, as they did not have the overhead of orientating to the physical table. Six participants mentioned that they preferred interaction with the physical object over air grasping as they felt they had better control and accuracy. One of the participants reported feeling a break in presence when he noticed his virtual hand was intersecting with the geometry of the virtual object using air grasping. Participants comments about air grasping include:

> "I prefer air grasping because I don't have to be constrained to a physical position."

> "Air grasping felt so fake. It didn't feel as good as passive haptic provided by the physical prop."

Out of 16 participants, 10 participants supported interaction with the physical prop was more realistic and less prone to errors for interaction. Six participants mentioned that although reaching for physical object was cumbersome and grasping was sometimes difficult, the feeling of touching a physical object improved presence in the environment. The following are representative comments about the haptic interaction:

“I like the haptic feedback while grasping the virtual objects. Maybe if there was way to differentiate the weight of different objects it will be more realistic. The physics remained consistent when compared to air grasping.”

“Interaction with the prop felt more realistic as the shape resembled the physical prop.”

# 5. EXPERIMENT 2

In virtual reality (VR) systems, motion tracking technology is often used to allow users to interact with virtual environments using physical movements and gestures. Generally, a one-to-one mapping between physical and virtual movements is preferred to enable a high sense of realism. Perfectly matched head tracking can allow users to view the virtual world using normal physical walking and turning, and hand tracking can allow interaction with virtual objects via a virtual hand that matches the position and orientation of the physical hand. In some cases, however, designers or users may find it beneficial to deviate from one-to-one mappings. For example, practical constraints such as limited physical space or tracking area have led to researchers to use scaled walking to allow users to use physical walking to traverse virtual spaces that are larger than the physical space (e.g., [34]) or to apply rotational gains to physical turning to help keep a user within the preferred tracking area (e.g., [35]). In other cases, “magic” or “hyper-natural” interactions might be preferred to make certain interactions easier or more convenient [36]. For example, the Go-Go technique applies a non-linear scaling to hand motion to allow users to virtually reach far away objects [37], and amplified head rotations can allow users to virtually turn all the way around while limiting physical effort [38].

All of these examples make use of scaled interactions that adjust the mapping between tracked motion inputs and the corresponding virtual motions. For certain applications, such as with hyper-natural techniques like the Go-Go technique, it may be expected that the user is aware of the scaling to effectively use the interaction technique. However, when the goal is to preserve the user’s sense of realism or presence in the experience, it might be preferred that users do not notice discrepancies in simulation’s fidelity. For this reason, it is important to study how well people can notice discrepancies in modified interactions (e.g., [21, 23, 24]). With the growing popularity of VR technology and affordable motion tracking technology, scaled interactions can enable interactions with 3D objects via natural hand movements using tracked hands, controllers, or physical props. Thus, our research focuses on the perception of scaled interactions for object-manipulation tasks using direct hand interaction.

We conducted an experiment to study how well different degrees of scaling can be detected for a variety of object movements involving translations and rotations with varying degrees of freedom (DOF) of motion. In our study, participants moved a physical object while observing the movement of a corresponding virtual object through a head-worn display. Participants had to indicate whether the visual motion was faster, slower, or the same as the motion of the physical object. Through this work, we address three research questions:

- How well can users detect scaled motions for varying magnitudes of scale factors for different interaction types?
- Does the amount of interaction (or time spent interacting) affect the ability to detect scaled motions?
- How do different scale factors affect performance for 3D object manipulation tasks?

### 5.1 Goals and Hypotheses

For practical applications of scaled interactions for direct object selection and manipulation tasks, larger scale factors ($S > 1.0$) could be used for cases such as allowing reaching for a virtual object that is farther away in the virtual world than could be physically reached (e.g., [37] [39]). Similarly, moving a virtual object a larger amount while reducing the necessary physical movement might be useful for reducing the necessary amount of physical effort or to prevent movement of a physical passive-haptic prop [1] beyond a the range for comfortable physical interaction. Similarly, smaller scale factors ($S < 1.0$) might be desirable to help match physical and virtual touching with a passive-haptic target [23] [24] or to encourage movement of a physical prop to a preferred location.

The primary goal of this research was to understand whether participants could distinguish between different levels of scaled interactions as being different than normal one-to-one movements for direct object manipulations. We hypothesized the existence of a range of values around one-to-one ($S = 1.0$) scale factors for which participants could not reliably distinguish whether the motion differed from normal movement. We also investigated whether the detection thresholds would vary based on different types of interactions, as prior work with 2D graphical value adjustments has found the perception of adjustments to vary based on interaction type (e.g., [40]).

A secondary goal of our research was to study whether scaled object motions would affect performance or adjustment behaviors during object manipulation tasks, and whether these differences varied based on different types of interactions. Based on other research manipulating CD ratios, we expected higher values of scaling to result in more errors and require more corrective behavior than lower scaling.

Finally, we sought to study whether perception of motion realism might be more easily "tricked" during brief interactions with limited opportunity for careful analysis of motion realism. We hypothesized that detection accuracy of scaled interactions would be greater if users could continually perform object movements and study the motion.

### 5.2 Experimental Task and Environment

To focus on our research goals, the experiment had participants complete tasks where a tracked physical object (a plastic bottle) was used as a controller for a virtual object. An appropriate target representation was shown for each interaction type. For both *slider* interactions, a virtual line on the slide track indicated the target location. For *tabletop object placement*, a bull's eye target was shown on the table. In case of the dial, participants aligned a notch indicator on the dial with a line pointing to the target direction. For the joystick, a line with semi-transparent object was shown to indicate the target orientation. Figure 5.2 includes representations of these target destinations for the interaction types. For all interaction types, participants performed the manipulation task by moving the virtual object to the indicated target position/orientation. This task was constrained for accuracy such that participants were required to match the object to the intended target to finish.

After the object manipulation, participants then had to choose whether the motion felt *normal*, *slower than normal*, or *faster than normal*. Thus, the primary measure was percentage of correct responses for each scale factor for each interaction type. In addition, we recorded motion behaviors so we could assess errors and corrective behaviors (e.g., overshooting beyond the target value and adjusting the movement).

To assess differences in extended use as compared to immediate perception with limited opportunity for the participant to test the motion and perceive differences, each experimental trial included two perception sub-tasks. First, participants completed the *quick perception judgment* task, which required an immediate object movement while a timer was shown to provide a sense of time pressure. After each *quick judgment* task and providing a response, participants were permitted to freely move the object (with the same scale factor and interaction type) in any way without a target or time pressure. This was the *free motion judgment* task, and participants were again asked to provide responses for motion perception.

### 5.3 Experimental Design

The experiment tested perception of object motion with different scale factors applied to different types of object interactions. The experiment followed an 12x5 repeated measures design with 12 levels of scale factor and 5 interaction types. The values of scale factor, $S$, ranged from 0.25 to 3.0 in increments of 0.25. When $S > 1.0$, the virtual object would move farther/faster than the physical object, whereas the virtual object would move less/slower when $S < 1.0$. Note that this range includes $S = 1.0$, where movements of the physical and virtual objects matched. Also, fewer low scale factors ($S < 1.0$) were compared to larger high scale factors ($S > 1.0$), as there are only three such values when incrementing by 0.25 between 0.0–1.0, but on the other end, there are eight factors between 1.0–3.0 with $S > 1.0$. The reason for this is that we chose a linear scale for value intervals and wanted to allow up to the maximum factor of 3.0 The value of 3.0 was chosen as a maximum limit because we sought to test a wide range of values where detection of scaled motions might be easy or difficult (we found higher values resulted in amplified movements that were overly sensitive to small changes of the physical object, which would make it easy to perceive the scaled movement).

For the selection of interaction types, our approach was to cover a variety of types of virtual movement controlled by a freely placed physical object. We selected object motions constrained by

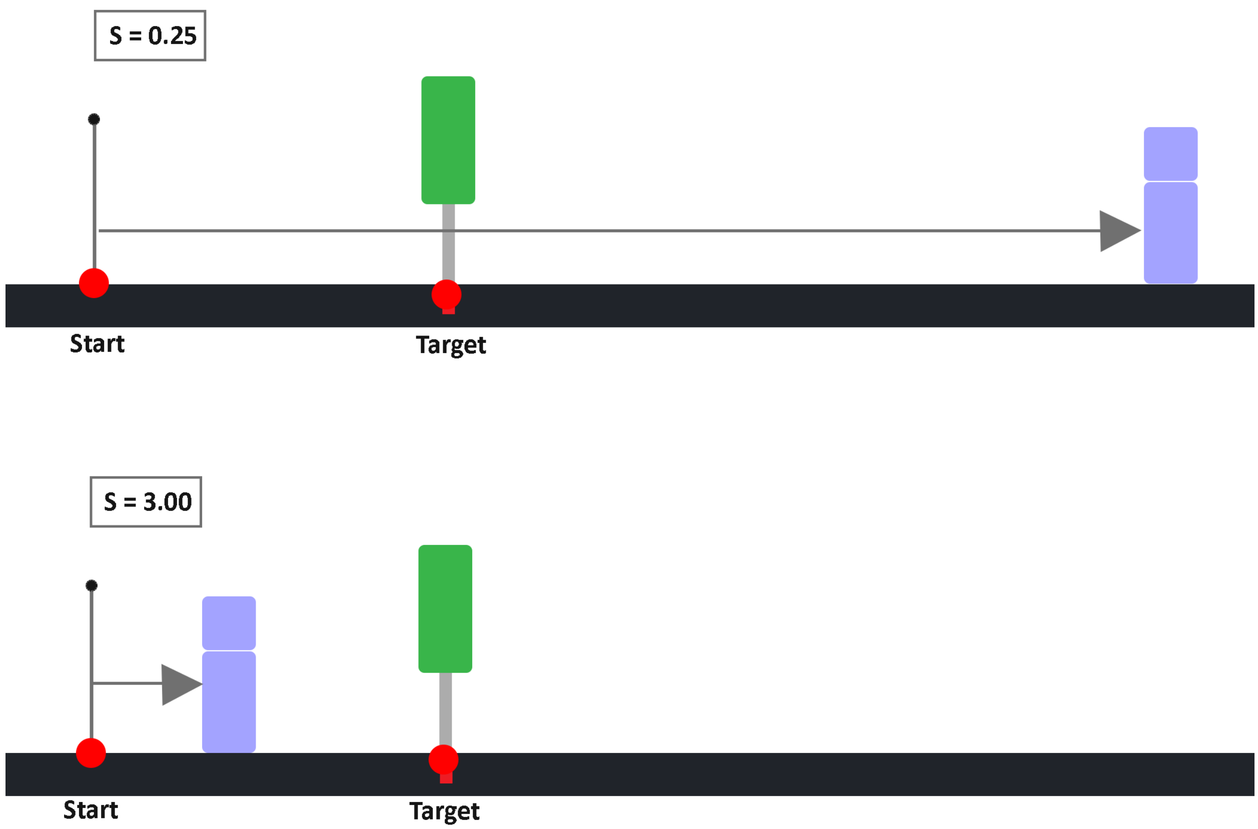


Figure 5.1: A diagram demonstrating scaled interactions. Scaled interactions change the mapping between physical and virtual objects. Here, the blue rectangle represents the position of the physical object, and the green object is the position of the corresponding virtual object (a slider from the study) when the physical object is moved with a scale factor of 0.25 (top) or 3.0 (bottom).

different degrees of freedom (DOF) with either translational or rotational movements. As shown in Figure 5.2, the following interaction types were tested:

- *Horizontal Slider*: An object with a cylindrical handle that slides along a linear track in front of the user. The object translates in 1 DOF to the left or the right.

- *Depth Slider*: An object with a cylindrical handle that slides along a linear track in front of the user. The object translates in 1 DOF toward or away from the user.

- *Tabletop Object Placement*: An object that can be moved along the horizontal plane or up and down. The object can translate in 3 DOF but with the virtual table as a constraint.

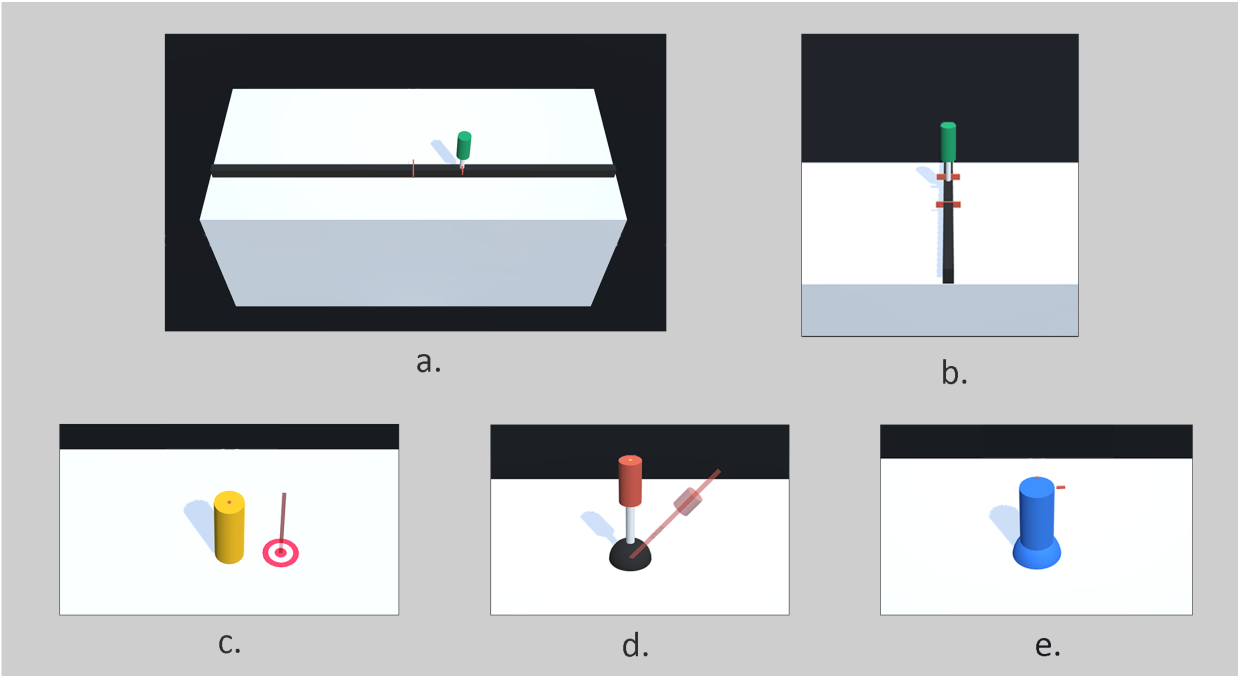


Figure 5.2: The image shows the virtual interaction types used in the study. This shows (a) horizontal slider, (b) depth slider, (c) tabletop object placement, (d) joystick, and (e) dial rotation. The target visuals are also included in each image.

- *Dial Rotation*: An object with a cylindrical handle that can only rotate in 1 DOF about the vertical axis (yaw).
- *Joystick Rotation*: An object with a cylindrical handle that can rotate in 2 DOF (pitch and roll), similar to a traditional computer joystick controller.

## 5.4 Apparatus

An Oculus Rift CV1 was used as the head mounted display (HMD) for this study. An Optitrack motion capture system consisting of 12 Flex-13 cameras was used to track six degrees-of-freedom (DOF) of the physical bottle and Oculus Rift HMD (the in-built Rift tracking was not used). At all times during the study tasks, participants held the physical object in their right hand. The participant's hand was not tracked, and no representation of a virtual hand was shown in the scene. Participants used Oculus touch controller in the left hand to select responses (see Figure 5.3). The software application for the study was developed with the Unity game engine and ran on a computer running 64-bit Windows 10, a 3.4 GHz Quad Core processor, and a GeForce GTX 1070 graphics processing unit.

Figure 5.3: The physical setup used for the scaled interactions study.

## 5.5 Participants

Eighteen participants (eleven males and seven females) participated in the study. All the participants were university students aged between 20 and 24 years. All the participants reported having good knowledge on computers and technology. Twelve of the eighteen participants reported playing some 3D video game every week. And eight participants reported not having any prior experience with VR before taking part in the study.

## 5.6 Study Procedure

The study was approved by our organization's institutional review board (IRB). Upon arrival, participants provided signed consent before continuing. They then completed a short background questionnaire. Next, participants were introduced to the equipment and familiarized with the study task. In a tutorial session, participants performed three trials from each of the five interaction types. For each interaction type in the tutorial, the participants experienced the slowest (0.25), the fastest (3.00), and normal (1.00) motion scaling to clearly understand the differences and the appropriate answers.

After the tutorial session, participants were asked to take a short break before continuing to the main trials. Each participant experienced a total of 80 object manipulations for the main trials, each with a unique combination of interaction type and scale factor presented in a random order. The main study trials were divided into three parts with two short breaks (up to five minutes) at equal intervals. To start each trial, the application showed a "Start" message and required the participant to press a button to confirm and begin. After every trial, the experimenter physically reset the object to the default position at the center of the table before each trial. After all trials, the experimenter conducted a short semi-structured interview to collect additional feedback from the participant. The entire procedure took approximately 60-75 minutes.

## 5.7 Results and Discussion

We report the results for the perception task based on correct classification of interaction scaling as either fast ($S > 1$), slow ($S < 1$), or normal motion ($S = 1$). We also considered manipulation task performance based on speed and the need for corrective adjustments.

An item of note is that while the study tested all five interaction types as previously described, there was a discrepancy in the implementation when applying the scale factors for the *joystick rotation* type. The cause was related to the virtual joystick moving through the virtual table for high-value scale factors, so different levels of scaling were calculated for this interaction. While the overall trends with the joystick interaction results were similar to the results of the other interaction types, the discrepancy in scale factors makes it difficult to consider this interaction in a meaningful way along with the other interaction types that all used the same scale factors. For the sake of simplicity and avoiding misinterpretation, we do not include the results for the joystick interactions in this analysis and report.

### 5.7.1 Perception Range for Scaled Interactions

To understand when participants had difficulty correctly classifying the scale factor as normal, we calculated the percentage of correct judgments at each increment of the scale factor for the different interaction types. The results for both the *quick perception* and *free motion* judgments are shown in Figure 5.4. Visual inspection shows a clear U-shaped trend with reduced judgment accuracy for scale factors close to 1.00. This trend is observed in all interaction types, with minor differences among them. We also see spikes in accuracy at 1.00 for most interaction types, which is because most (67.5% on average) of the incorrect responses in each range of uncertainty were answers of "moving as normal". However, we also note that a small percentage (6%) of low-scale ($S < 1.0$) trials were misclassifed as "fast" in the *quick perception* judgments, whereas no high-scale trials ($S > 1.0$) were misclassifed as "slow". This demonstrates that with low scaling, participants were not always distinguishing only between one-to-one and scaled motions, but they sometimes were either guessing or experiencing significant misperceptions.

To better assess the range where participants had the most trouble correctly classifying the scaling, we tested how close the correct-response percentages were with respect to the percentage that would be expected due to chance alone. This was done at each scale factor for each interaction type using a chi-square goodness-of-fit test to compare the actual correctness percentage to the expected one-third rate (as there were three possible responses). The test results are included in Figure 5.4, with starred results indicating results that were significantly different from chance. For all interaction types, we always see the highest and lowest scale factors have significant differences, which is because participants were generally highly accurate with extreme levels of scaling. In the middle range with lower correctness rates, a lack of a significant difference indicates that participants did not answer correctly at a rate significantly better than guessing. Therefore, we use this range of non-significant differences as a means of approximating a range of scale factors where it is difficult to perceive scaled interactions. These ranges are indicated by the orange bars to the left of the charts in Figure 5.4. We note that the 1.0 scale factor is always included in this range because participants were mostly responding with the “normal” response in this range (75.0% of *dial rotation*, 58.5% of *tabletop object*, 71.8% of *horizontal slider*, and 64.5% of *depth slider* responses were ”normal“ in the marked ranges). We also note that these ranges of uncertainty also sometimes include the scale factor of 1.25 even when this scale level achieved a response rate significantly different from chance (this is the case for the *depth slider*, as shown in Figures 5.4e), which is acceptable because the correctness rates for these scale factors are significantly *worse* than chance—providing even stronger evidence that these levels should be included within the bounds of uncertainty.

Overall, these results show evidence of significant uncertainty of judgments for scale factors in the range of 0.75–1.75 for the *depth slider*, a range of 1.00–1.75 for the *tabletop object*, and a range of 0.75–1.50 for both the *horizontal slider* and the *dial rotation* interactions (see Figure 5.4). This supports our primary hypothesis that some levels of scaling can be difficult to perceive. We note that these values do not indicate absolute thresholds for scale detection, as the level of precision was somewhat coarse given the 0.25 increments in scale factor. It is also important to not that although we report these ranges based on significance testing comparing correct response rate to the rate of chance, the U-shaped trends suggest a lack of hard thresholds. The results demonstrate a degree of uncertainty even for more extreme scale factors. For example, in the *quick perception* task, response accuracy for the *depth slider* only reached 75% even for the highest scale factor of 3.0, and a similar 75% judgment accuracy was seen for *dial rotation* up to a factor of 2.50.

### 5.7.2 Quick Perception and Free Motion

We also addressed our hypothesis of whether perception of motion scaling would differ based on the amount of time and experience spent testing the motions. To do this, we compared differences in correct responses for the initial *quick perception* judgments and the following *free motion* judgments. We compared responses for these two judgments using a two-way repeated measures

ANOVA that also accounted for differences due to the interaction types (excluding the joystick type, as previously explained). This test considered the total number of correct responses for each interaction type regardless of scale factor. The data met the assumptions for sphericity and normality for parametric testing. The analysis found significant evidence of more correct responses in the *free motion* task as compared to the first *quick perception* task, with test results providing $F(1, 15) = 22.10$ and $p < 0.001$. On average, the *free motion* judgments had $13.1\%$ more correct responses than the *quick perception* judgments. No significant was detected due to interaction type, and no interaction effect was found between the two factors.

This finding supports our hypothesis that it can be more difficult to correctly classify the type of motion scaling for a single immediate scaled action than with additional movement and attention to the interaction. Also consider that even for the *quick perception* tasks, participants were always acutely aware that scaling was often being applied to the interactions. That is, participants always had focused attention on the motion, as this was the nature of the experiment, and we had explicitly explained that different interactions would be scaled. As such, we expect that it may be even more difficult to detect scaling if the participants were less attentive to the motions while considering their physical senses and proprioception. In other words, this significant difference in ability to distinguish scaling may be even stronger when comparing attentive actions to instances when users are preoccupied with other goals or if they are unaware that scaling would be applied.

### 5.7.3 Manipulation Task Speed

We also consider how interaction scaling influences performance on the object manipulation tasks. We do not consider accuracy for the 3D manipulation task because it was constrained such that participants were required to match the virtual object to the given target position or orientation. We could consider differences in task times, but we would obviously expect it to take longer to move greater differences, and the scale factor influences the amount the object must be physically moved. That is, objects must be physically moved more with lower scale factors and less with higher scale factors to achieve the same amount of virtual movement. To account for this and normalize for distance, we analyzed the *speed* of physical object movement as the ratio of physical distance to completion time.

We tested whether different types of scaling influence manipulation speed by comparing high scaling ($S > 1.0$) and low scaling ($S < 1.0$) relative to the speed of normal motion ($S = 1.0$). For this analysis, we do not compare interaction types to each other because the interactions were fundamentally different, thus making the comparison not meaningful. Thus, for each interaction type, we ran a paired t-test for the percentage of physical speed for the high and low scaling groups relative to the $S = 1.0$ group.

No differences in speed were detected for the *tabletop object placement*, *depth slider*, or *horizontal slider* interactions. However, the t-test for *dial rotation* found the physical actions for the low-scale trials to be significantly faster than the high-scale trials with $t(15) = 3.31$ and $p = 0.02$ after Bonferroni correction for the multiple tests. It may seem surprising to observe a difference between high or low scaling after normalizing for physical movement distance, but this result may be attributed to the nature of the hand control needed for the *dial rotation* interaction. While the other interaction types could all be performed with continuous motions (regardless of physical distance), a person has a limited angular range of wrist rotation when rotating a dial. Therefore, for covering large angular distances with the dial, the user had to repeatedly grip the dial, turn the wrist, release, and re-grip to continue turning. In the case of low scale factors that require a larger amount of physical turning, users realized the need for a large amount of turns, and thus sped up the turning by using a sequence of quick turns/spins. This demonstrates that the effect of different types of scaling on interaction performance and behavior is heavily dependent on the specifics of the interaction motion.

### 5.7.4 Corrective Adjustments

In the real world, people generally use direct hand control for object manipulation for almost any 3D interaction in daily life. Thus, applying scaling could be expected to affect the accuracy or efficiency of direct interactions. This would especially be the case for high scale factors ($S > 1.0$) where the sensitivity to physical motion is increased, whereas for low scale factors ($S < 1.0$), controls can be more precise than normal one-to-one movements. Because accuracy was constrained for the manipulation task in our *quick perception* task, we considered instances of corrective adjustment during manipulation. That is, we tested movement behavior where participants adjusted the position/orientation of the virtual object past the given target transform, and thus had to reverse the direction of motion to correct the manipulation. We counted the number of times the virtual object passed the intended target value in either direction. These corrective adjustments could happen multiple times per trial due to increasing and decreasing adjustments.

Figure 5.5 shows a summary of the corrective adjustment results. We compared the percentage of occurrences of corrective adjustments for high scale factors and low scale factors relative to one-to-one movement for each of the four interaction type using paired t-tests. The tests found significantly more corrective adjustments with higher scale factors ($S > 1.0$) than lower scale factors ($S < 1.0$) for the *horizontal slider* interactions with $t(15) = 4.67$, *depth slider* interactions with $t(15) = 3.73$, and *dial rotation* interactions with $t(15) = 3.09$. These three interactions were significant at the $p < 0.05$ level with Bonferroni correction. No significant difference was detected for the tabletop object placement interaction. Thus, our hypothesis was confirmed for three of the four tested interactions, demonstrating that up-scaling motion can reduce precision of 3D manipulation. The absence of this result for *tabletop object placement* may be related to the fact that this interaction made use of the same 3 DOF for the virtual movement as the physical movement. That is, perhaps participants were able to maintain better control of scaled motions because the virtual object could be freely moved on the table just as the physical object moved on the table, whereas the other interaction types used the physical object as a controller for different DOF movement of the virtual objects. If this is the case, users might be more sensitive to interaction scaling when using less familiar motion controls or interaction metaphors, but further research would be needed to address this hypothesis.

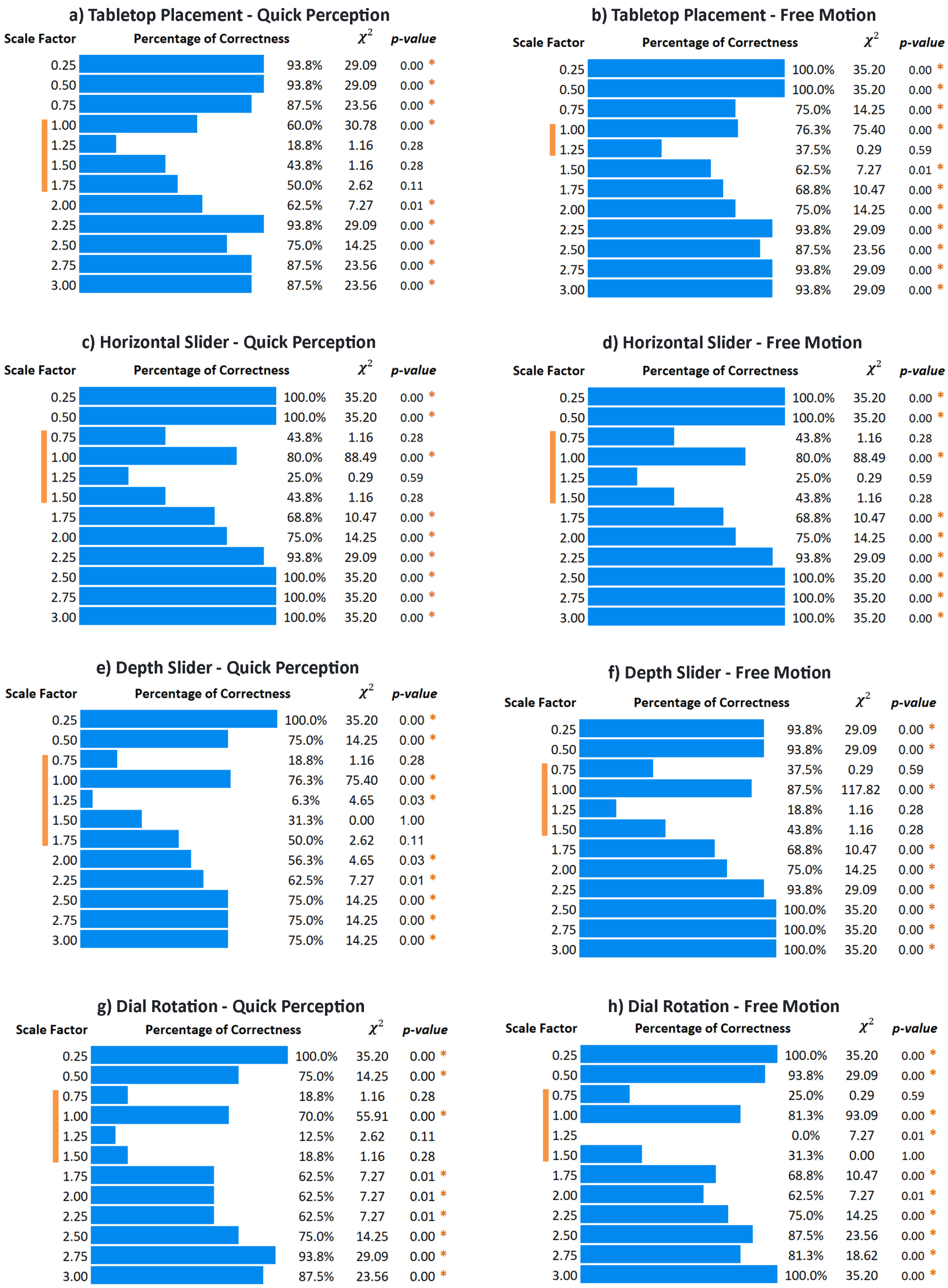


Figure 5.4: Percentage of correct responses for the perception judgments with different scale factors for different interaction types. The *free motion* judgments (right column) were significantly better than the *quick perception* judgments (left column). Stars indicate response rates that were significantly different from chance, and the orange bar on the side of each image shows the range of uncertainty based on significance testing.

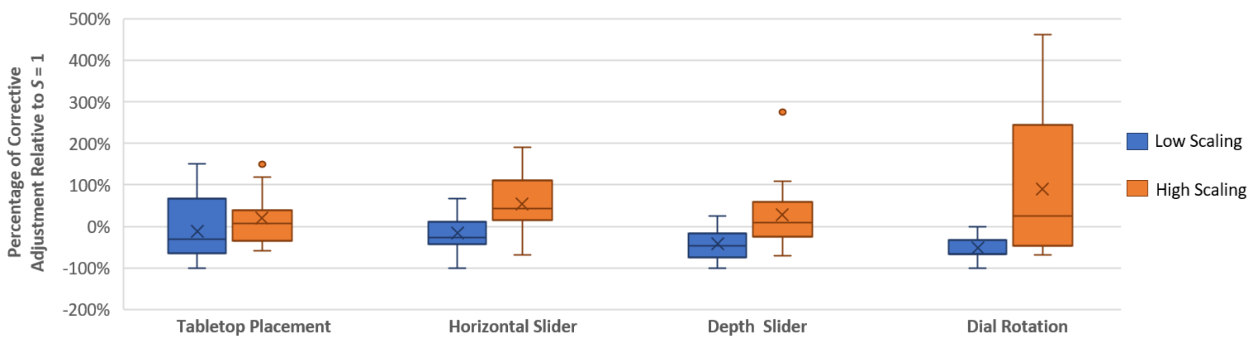


Figure 5.5: Percentage of trials with corrective adjustments during the quick perception manipulations. Significantly more corrective adjustments were observed with high scaling than low scaling for all interactions except for *tabletop placement*.

# 6. EXPERIMENT 3

## 6.1 Goals and Hypotheses

Although past research works have showcased building complex systems to convey the information of object weight, it is a relatively unexplored space of using vibro-tactile feedback to convey or influence the sense of the weight of an object in virtual reality. Importantly, our research aims to prototype a light-weight haptic system to be worn around the user's arm to work along with a passive-haptic object for object maipulation tasks. Hence, it is essential to understand the relationship between the level of haptic actuation needed to be applied and its effect on the human perception of weight. The goals of this experiment are:

- To test the effect of various levels of haptic actuation on the perception of weight of a physical object (between two 250g objects).
- Compare and report trends or deviations along a range of object weights (between objects of weight 220g, 250g, 280g, and 310g).

From a set of formative studies conducted, we noticed that a particular level of haptic feedback applied to the user's arm changed their judgment of perceived weight. Thus, gathering more data points and recognizing a pattern in the effect observed was essential for our research. We hypothesized that users would find it difficult to detect closer weight differences but how much was a point of interest. Also, we sought to study whether a certain level of haptic actuation corresponded to the perceived weight of the object. For example, a low frequency actuation could make an object feel more heavier than higher frequency actuation.

## 6.2 Experimental Environment and Task

The user study was conducted in a space amidst 12 OptiTrack Flex 13 cameras capable of doing three-person full body motion capture. Five identical motion tracked water bottles were placed on the table. Each object differed from another by a small difference in weight of 30g.

The weight of each water bottle was measured using a digital weighing scale. Sand was used to add precise weight to the water bottle. There were five water bottles weighing, 220g, 250g (2), 280g and 310g. Participants were asked to be seated in an office chair with armrests in front of a rectangular plastic table. Oculus CV1 was used as the virtual reality headset for the study. Participants were interacting with the physical props in their dominant hand, and they held an Oculus touch controller, on the other hand, to select options on the response board.

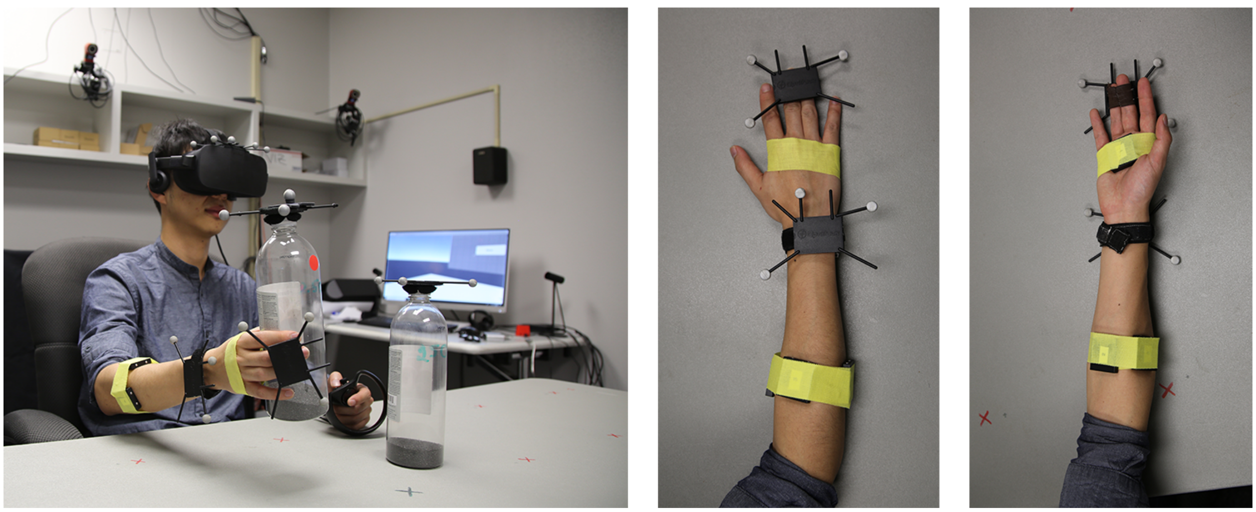

Figure 6.1: The physical setup for the weight perception study. This includes a table, a tracked bottle, four vibrotactile units on the user's forearm, OptiTrack markers, and an HMD.

During the study, participant's wrist and finger motion were tracked to simulate a virtual hand in the game environment. Basslet, a wireless vibro-tactile actuator was used to provide haptic feedback to the user's arm. Four basslets units used. The basslet units were capable of conveying actuations in the range of 50-250 HZ. These vibro-tactile units were attached to user's arm using an athletic tape, and the necessity of tape was to make sure the units touched the user's skin but are not attached too tight to influence their normal interaction experience. All four basslet units were attached to the user's forearm, and the haptic feedback was applied to four specific locations. Specifically, one on the user's palm, and other three units covering the major muscle groups in the forearm (see Figure 6.1).

The game environment was built with Unity game engine. The virtual environment was carefully made simple with an open space with a white rectangular cuboid representing the physical table. A virtual instruction board was shown in front of the virtual table. This board displayed the status of the study showing message such as "Ready", "Done" and "Take a break!". The virtual board was also used to record user responses for the study by using the touch controller.

As part of the user's task, they compared two out of the five physical objects and positioning the physical objects was done by the experimenter. Once the experimenter has set up the objects to be compared, he pressed 'continue' on the Oculus remote to proceed with the study procedure. The experimental task for this study was to compare the weight of the two physical objects by lifting and placing them on the table using their dominant hand. Once the participants were convinced of their choice, they pressed a button on the controller to proceed to the response board. And here, the participants selected the side of the object, which they felt heavier.

### 6.3 Experimental Design

In the previous experiment, we studied whether participants were able to detect the difference in virtual motion by varying the scale factor (control-to-display ratio) of the interaction. For understanding the influence of vibro-tactile feedback on the perception of weight of the physical object, we needed to change different actuation levels on the physical object and change object weight to recognize a pattern (see Figure 6.3). So, we compared with the following variables:

- Test Object Actuation Level (TAL): From the results of the pilot studies conducted to understand perceivable levels of actuation with the vibro-tactile units (Basslets). We chose three frequency levels of a sine wave tone. Our participants experienced a feedback of 50 HZ, 80 HZ, or 110 HZ when they lifted the physical object for comparison.

- Reference Object Actuation Level (RAL): We also varied the level of actuation on the reference object. It was same as 50 HZ, 80 HZ, or 110 HZ applied to the user's arm when they pick up the reference object during the task.

- Object Weight (OW) : From the formative evaluations conducted, we identified the effect of

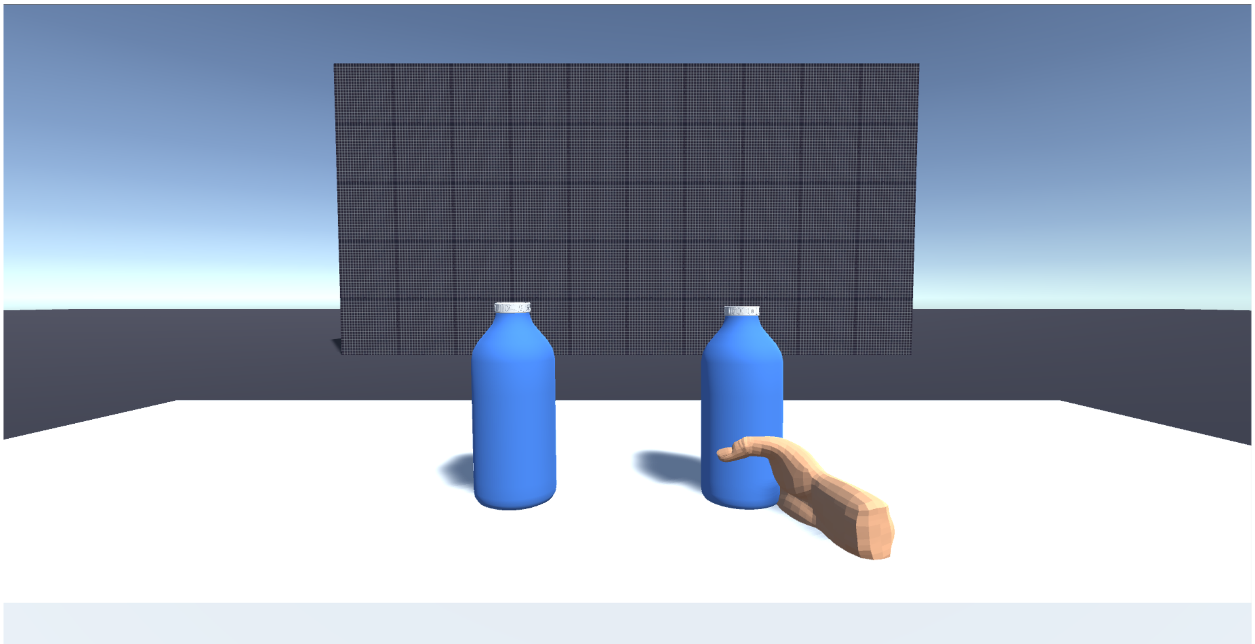

Figure 6.2: Simulation environment showing two visually identical bottles placed on the side to each other. One bottle corresponds to the reference object and another corresponds to the test object.

actuation was perceived differently with respect to the physical weight of the object. So, we built five identical physical objects weighing 220g, 250g (2), 280g, 310g. The weight of the reference object was always constrained to 250g. The reference object was compared with 220g which is lower than its weight, and 280g, and 310g objects which were heavier than the reference object. Also, we added a same weighted object (250g) to be compared with the reference object, to learn more about level of actuation applied to these objects. Results for the 250g object are discussed separately.

The experiment followed a within subjects, repeated-measures design. Where each participant experienced all possible combinations of above mentioned variables. The experimental procedure was broken into three segments, each segment consisted of 24 trials adding to a total of 72 trials for the complete study (3 TAL x 3 RAL x 4 OW x 2 Repeats). The order of the trials was randomized to eliminate confound of learning effects during the study for each participant. Also, position of the reference object was randomized between left and right side. There were 36 identical trials in

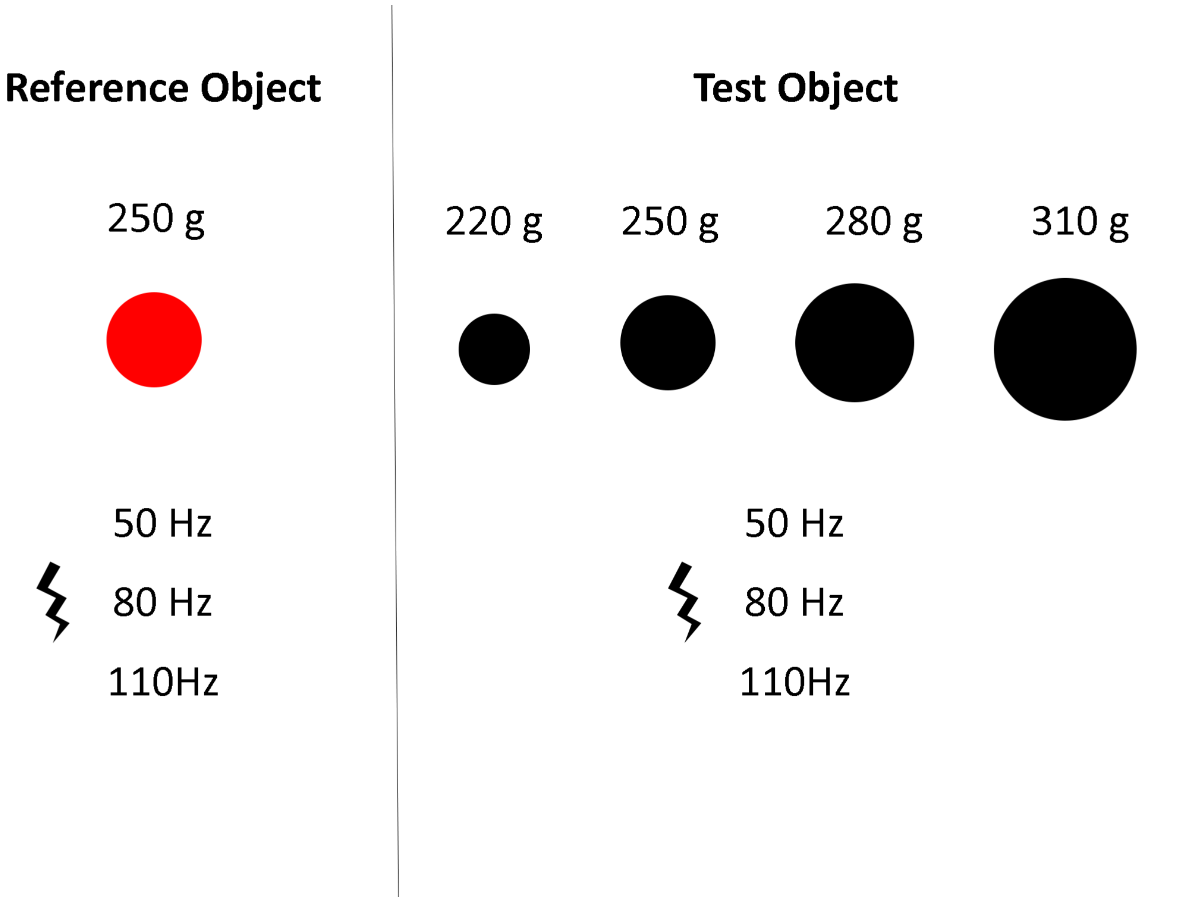


Figure 6.3: A reference object with constant physical weight was compared with four test objects with different physical weights and three actuation levels.

which a new combination of test object actuation level, reference object actuation level and object weight was presented. And we repeated the same trials once more to collect more data to test for consistency in the responses. To calculate the effects of the independent variables on perception of weight, we considered percentage of correctness to the ground truth (physically heavier object is the heaviest) and time taken for choosing the heaviest of the objects.

### 6.4 Procedure

Participants were asked to be seated at a table, and the experimenter explained the informed consent form, the background of the research, study procedure, and the equipment that they will be using for the study. Once the participants agreed to proceed with the study, the experimenter asked the participant to fill a participant background questionnaire, which included questions such as participant's age, gender and occupation, their professional background and their experience with 3D games and virtual reality. On completion of the questionnaire, participants were equipped with the vibro-tactile actuators on their arm over the locations mentioned in the experimental setup section.

A test trigger of the actuators was done to verify good working condition of all the actuators on the arm, and the experimenter confirmed with the participant whether they are comfortable with proceeding with the study. Then, the participants were helped with strapping on the trackers for simulating hand and finger motions. The experimenter showed the working of the touch controller buttons and way to place it in their non-dominant hand. As the last step of the setup, the participants were handed over Oculus Rift headset to put it on their head, and a confirmation of a vivid display was done. Before proceeding into the main study, the participants were given three random trials to get comfortable with the task; button pushes on the controller and timing for each trial. On completion of the practice, the participants were asked to take off the HMD to a short time span, before proceeding to the main study.

The main study consisted of three segments each with 24 trials. Moreover, there were two break sessions of five minutes provided in-between the study segments. The participants were also informed about stopping the study if they were feeling any discomfort, pain, or soreness in their arm. Before beginning every trial, the word 'Ready' was displayed on the virtual board. During this time the experimenter manually arranged the two physical objects those need to be compared by getting a cue from the computer monitor. Moreover, the participants did not have visibility of which object was being moved. Once the experimenter has completed setting up the objects, he pressed the next button on the Oculus remote to enable the participant to see the two objects in the virtual environment. Then, the participant continued picking up and placing the two objects on the virtual table to decide on the heaviest object. Participants were told that they could take as much time as they want to decide their choice of the heavier object, while they continue to pick and place the objects. After the participant chose the heaviest object, he/she pressed the button on their controller to proceed with viewing the response board. When the participants were viewing the response board, the visuals for the two objects were disabled. Then, the participant selected one of the two options displayed (either 'Left Side' or 'Right Side'). After the selection, a 'done' message was displayed to the user. Then, the experimenter acknowledged the end of the trial with a button press, to look for the next cue on the monitor for object placement. The time of the trial was recorded from when the participant had visuals of the two objects to selecting one the option for the heavier object.

At the end of three segments, participants were helped with taking off the vibro-tactile actuators, and a short semi-structured interview was done to collect more feedback from the participant. The interview guide had questions about the complete experience of the study, the rationale of selecting the object when both objects felt the same, and at last, the percentage of the trials that participants thought were with the same weight. The complete experiment took about 60 to 75 minutes.

### 6.5 Participants

Nineteen participants (14 males, 5 females) took part in the study. The participants' age ranged from 23 to 32 with a median of 26.0 years. Professional background of the participants was a mix of students, employees, and professors and in case of the students, three were from the computer graphics program, four were from computer science, two from management studies, and two were professionals working as UX designers. Participation was entirely voluntary, and no compensation was given. All the participants were right hand dominant, and they interacted with an object with their right hand and held the touch controller on the left hand. 13 out of 19 participants had previous experience with virtual reality ranging from trying few demos to an expert in the field.

### 6.6 Results and Discussion

We report the results of the weight perception task based on calculated correctness percentage. And, we considered two sets of data for simplifying our analysis of a three-independent variable task. First, when the test and reference objects were of the same physical weight but different

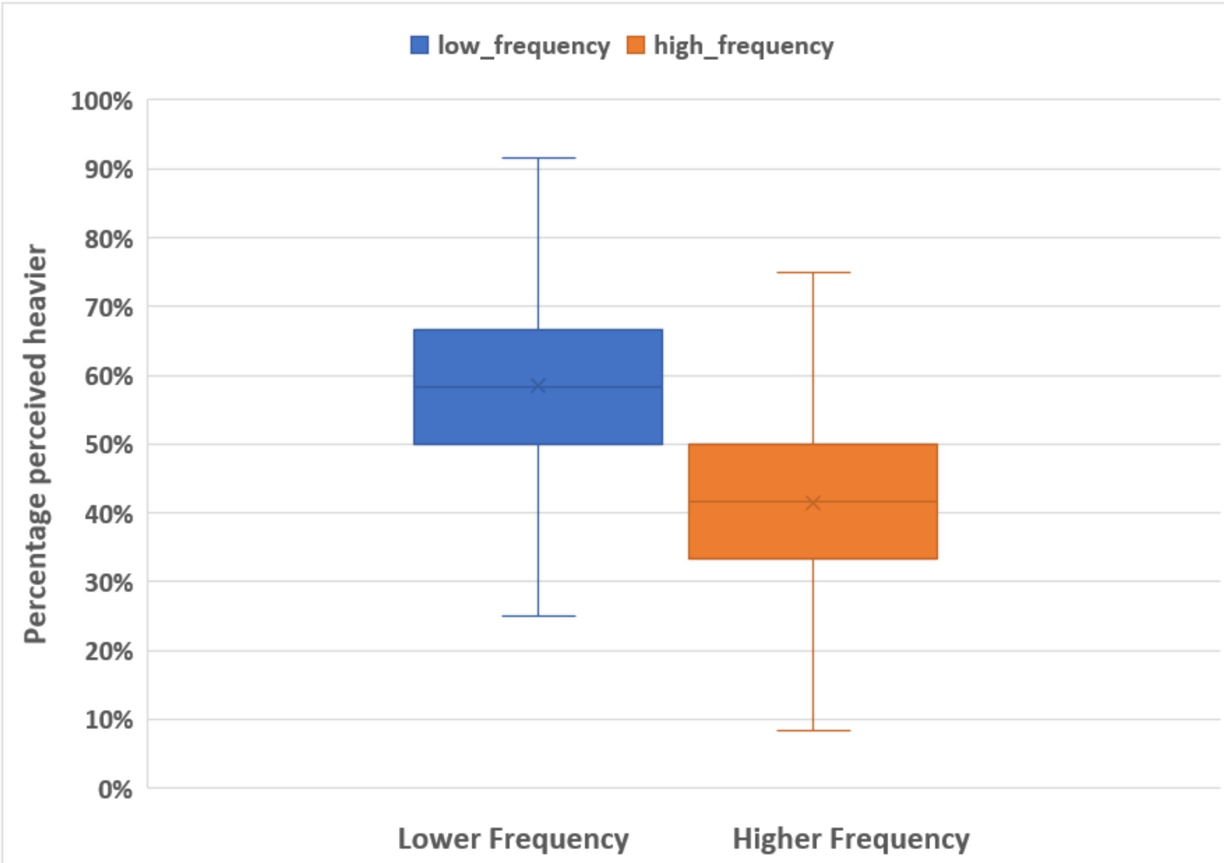


Figure 6.4: Graph showing percentage of trials when the weight of reference and test object was same.

in the level of frequency actuation. Second, when both the weight and frequency of the test and reference objects were different. To present results based on the effect of the level of frequency on perception of weight, we did not consider the data points with same frequency level applied to both test and reference objects.

### 6.6.1 Comparing Same Physical Weights

In this case, both the test object and reference object weight were 250g. We included such a test in a two-alternative forced-choice task to better understand the role of frequency in the weight perception task. When the participants attempted the same-weight task, the average time taken for judging the heavier object was significantly higher than cases when the participants tried a different-weight task. Participants took an overall mean of 27.744 seconds for making the decision in the same-weight task, whereas in a different-weight task they took less time to make a decision, $17.18 - 22.08$ seconds in comparison to the same-weight task. In this scenario, no answer is correct as both the objects are of same physical weight. Hence, we considered user's choice which they felt heavier as the main rubric for the analysis. To test the effect of level of frequency in the same-weight segment, we grouped data points by the level of frequency of the user's choice. When frequency of the selected object was lower than the frequency of the not selected object, we grouped this case in the lower frequency group. And when frequency of the selected object was higher than the frequency of the not selected object, we grouped this case in the higher frequency group. Then we calculated the percentage of choices of higher and lower frequency group and listed the data across all the participants to observe the trend of which group of frequency level made the object feel heavier (see Figure 6.4).

We ran a paired t-test for the percentage of lower frequency trials perceived as heavier to percentage of higher frequency trials that were perceived as heavier. And found the lower frequencies were perceived significantly heavier than the higher frequencies with $t(18) = 2.17$ and $p = 0.04$ after Bonferroni correction for the multiple tests. And we plotted the data on a box-and-whisker plot showing the observed effect (see Figure 6.4). The observed behavior could be due to the constant thumping felt on the user's arm in a lower frequency trial, which possibly could make the user to exert more physical effort in picking up the object. Hence, we could potentially create a perceptual illusion of an object being heavier by simply applying a lower frequency actuation on the user's hand.

### 6.6.2 Comparing Different Physical Weights

Similar, to the categorizing followed in the previous section. We merged the experiment trials into four groups for a different-weighted task analysis.

- Lighter object with lower frequency
- Lighter object with higher frequency
- Heavier object with lower frequency

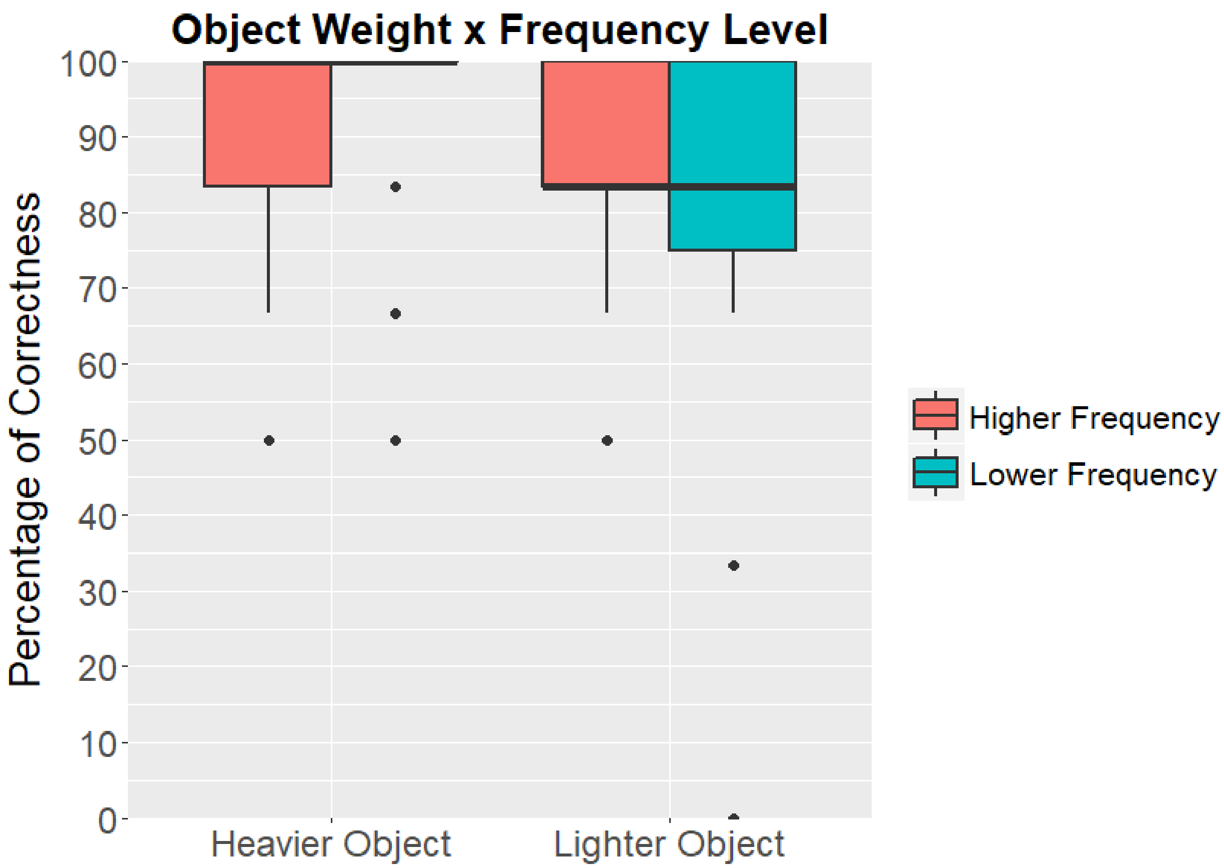


Figure 6.5: Graph showing percentage of trials when the weight of reference and test object was different.

- Heavier object with higher frequency

In this segment, both the test and reference objects differed by physical weight. In this case calculating the percentage of correctness was fairly easier based on the ground truth. Trials with different object weights and same frequency level were not considered for the analysis, as this research was primarily focused on testing the influence of haptic actuation on perception of weight and having same actuation level would not add value to the analysis. In the considered range of weights, there were two test objects which were heavier than the reference object (280 g, 310 g) and one object which was lighter than the reference object (220 g). Comparing the accuracy of the heavier test objects, the object with 310g had the highest level of correctness percentage due to a large weight difference with the reference object (60g). Also, to have an equal spread of data points along the weight range, we considered 280g object on the heavier end and 220g object on the lighter end in comparison to the reference object which was 250g. The chart (see Figure 6.5) show percentage of correctness based on object weight and frequency level when tested with the reference object. For our analysis and presentation of results, we use repeated-measures ANOVA tests and graphical plots to represent differences due to experimental variables. We present results with box-and-whisker plots where colored rectangles represents the interquartile range (IQR) and a horizontal black strip marks the median value. “whisker” lines in black extend from the rectangle to the extreme value that falls in an additional half-IQR after the IQR, or no whisker is shown if no points fall in this range. Black dots denote values beyond this range. For this experiment, the percentage of correctness results met the assumptions of normality and sphericity for parametric testing.

We ran a two-way repeated measures ANOVA with object weight and level of frequency as independent variables. But, the test showed no significance for the interaction effect between the frequency and object weight. However, the general trend observed showed trials with lighter object with lower frequency were accurate than lighter object with higher frequency. Which can be interpreted as, low frequencies influencing the weight to be perceived as heavier when compared to the reference object (250g). Similarly, heavier object with lower frequency have the highest accuracy which could mean the object was felt heavier when compared to the reference object(250g) and the user’s had no sense of doubt.

# 7. DISCUSSION & CONCLUSION

## 7.1 Summary

For a broad investigation on reuse of a physical prop, we conducted a multi-leg research addressing different dimensions of the problem. First, we dealt with refining a hand redirection technique that can help to map one physical prop to multiple virtual objects and interactions. The results for this experiment demonstrated that use of proxy prop was successful and convenient in a game environment allowing choice of interactions and free exploration. Many participants were interested in interacting with a real-world object, and their responses show they could keep track of their physical orientation in the real-world. Likewise, participants reported a higher sense of realism and control while interacting with a real-world object as compared to the no-haptic condition. This study helped in understanding user preference and experience of using passive-haptic interactions. However, continuous application of hand redirection techniques could cause larger hand offset and lead to a disruption in user experience. Implementation of one-to-one motion of the physical prop was making the object leave user's comfortable area of reach. Considering these limitations, scaling the amount of virtual motion was studied to keep the physical object from moving away from the user. In the following experiment, we conducted a controlled study to evaluate how well participants could differentiate varying levels of motion scaling for different types of object manipulation tasks. The results showed evidence of a range of uncertainty where it was difficult to correctly classify scaling that results in motions that are faster or slower than normal one-to-one object movements. Overall, the results demonstrated that it can be difficult to detect a moderate amount of scaling, but how much depends on the type of virtual interaction. The understanding of perception of scaled motions will help building experiences to reuse one physical prop and at the same time conserve the interaction fidelity. For example, In a tabletop interaction, the scale factor of 1.75 was perceived as normal. And using a scale factor of 1.75 required 42% less physical movement in comparison to the one-one movement of the object. To further explore possibilities of reuse beyond positional alignment and different interaction paradigm. We were motivated to build and test active mechanisms to work with a passive haptic prop which can cater to other dimensions of the virtual object such as object weight, size or texture. In the final experiment, we conducted an exploratory study to test the effect of vibro-tactile feedback on perception of weight of the object. And we observed that a lower frequency actuation applied to the user's hand can significantly make the object feel heavier than its actual weight. With influx of VR systems, motion tracking physical props has become easier. And the use of real-world props for interactions in VR applications have considerably increased in recent times. Our research enables repurposing of real world objects in simple, lightweight setups such as home entertainment and VR training facilities.

## 7.2 Future Direction

Continuing our current work, we would like to consider other aspects of prop reuse, such as making minor modifications to the passive haptic object or build a dynamic haptic proxy object which can transforms it's shape, size and weight in accordance with the mapped virtual object. Importantly, building low cost and accessible dynamic haptic props for VR consumers will be a driving motivation of this research. Studying habituation to scaled interaction as well as changes in scale factor after such habituation would provide useful knowledge for how scaling might influence performance or perception in real VR applications. Merits and challenges from our current research leads us to explore other feasible actuation methods such as use of pneumatics or dynamic weight distribution to vary the perception of weight of an object. Finally, incorporating the valuable research from the field of psycho-physiology will further help in building effective and practical virtual reality experiences.

REFERENCES


[1] B. E. Insko, M. Meehan, M. Whitton, and F. Brooks, *Passive haptics significantly enhances virtual environments*. PhD thesis, University of North Carolina at Chapel Hill, 2001.

[2] J. C. McClelland, R. J. Teather, and A. Girouard, "Haptobend: shape-changing passive haptic feedback in virtual reality," in *Proceedings of the 5th Symposium on Spatial User Interaction*, pp. 82–90, ACM, 2017.

[3] H. Benko, C. Holz, M. Sinclair, and E. Ofek, "Normaltouch and texturetouch: High-fidelity 3d haptic shape rendering on handheld virtual reality controllers," in *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pp. 717–728, ACM, 2016.

[4] C. D. Giachritsis, P. Garcia-Robledo, J. Barrio, A. M. Wing, and M. Ferre, "Unimanual, bimanual and bilateral weight perception of virtual objects in the master finger 2 environment," in *RO-MAN, 2010 IEEE*, pp. 513–519, IEEE, 2010.

[5] K. Minamizawa, S. Fukamachi, H. Kajimoto, N. Kawakami, and S. Tachi, "Gravity grabber: wearable haptic display to present virtual mass sensation," in *ACM SIGGRAPH 2007 emerging technologies*, p. 8, ACM, 2007.

[6] A. Zenner and A. Krüger, "Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality," *IEEE Transactions on Visualization and Computer Graphics*, vol. 23, no. 4, pp. 1285–1294, 2017.

[7] M. Tanaka, A. Misra, K. Oshima, S. Hashiguchi, S. Mori, F. Shibata, A. Kimura, and H. Tamura, "[poster] further experiments and considerations on weight perception caused by visual diminishing of real objects," in *Mixed and Augmented Reality (ISMAR-Adjunct), 2017 IEEE International Symposium on*, pp. 160–161, IEEE, 2017.

[8] K. Hinckley, R. Pausch, J. C. Goble, and N. F. Kassell, "Passive real-world interface props for neurosurgical visualization," in *Proceedings of the SIGCHI conference on Human factors*

*in computing systems*, pp. 452–458, ACM, 1994.

[9] M. Meehan, B. Insko, M. Whitton, and F. P. Brooks Jr, "Physiological measures of presence in stressful virtual environments," *ACM Transactions on Graphics (TOG)*, vol. 21, no. 3, pp. 645–652, 2002.

[10] B. Lok, S. Naik, M. Whitton, and F. P. Brooks, "Effects of handling real objects and avatar fidelity on cognitive task performance in virtual environments," in *Virtual Reality, 2003. Proceedings. IEEE*, pp. 125–132, IEEE, 2003.

[11] E. Burns, S. Razzaque, A. T. Panter, M. C. Whitton, M. R. McCallus, and F. P. Brooks, "The hand is slower than the eye: A quantitative exploration of visual dominance over proprioception," in *Virtual Reality, 2005. Proceedings. VR 2005. IEEE*, pp. 3–10, IEEE, 2005.

[12] E. Burns, S. Razzaque, M. C. Whitton, and F. P. Brooks, "Macbeth: The avatar which i see before me and its movement toward my hand," in *2007 IEEE Virtual Reality Conference*, pp. 295–296, IEEE, 2007.

[13] A. Lécuyer, "Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback," *Presence: Teleoperators and Virtual Environments*, vol. 18, no. 1, pp. 39–53, 2009.

[14] A. Lécuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet, "Pseudo-haptic feedback: can isometric input devices simulate force feedback?," in *Virtual Reality, 2000. Proceedings. IEEE*, pp. 83–90, IEEE, 2000.

[15] A. Lécuyer, J.-M. Burkhardt, and L. Etienne, "Feeling bumps and holes without a haptic interface: the perception of pseudo-haptic textures," in *Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 239–246, ACM, 2004.

[16] L. Kohli, "Redirected touching: Warping space to remap passive haptics," in *3D User Interfaces (3DUI), 2010 IEEE Symposium on*, pp. 129–130, IEEE, 2010.

[17] E. Ebrahimi, B. Altenhoff, L. Hartman, J. A. Jones, S. V. Babu, C. C. Pagano, and T. A. Davis, "Effects of visual and proprioceptive information in visuo-motor calibration during

a closed-loop physical reach task in immersive virtual environments," in *Proceedings of the ACM Symposium on Applied Perception*, pp. 103–110, ACM, 2014.

[18] M. Azmandian, M. Hancock, H. Benko, E. Ofek, and A. D. Wilson, "Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences," in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 1968–1979, ACM, 2016.

[19] D. T. Han, M. Suhail, and E. D. Ragan, "Evaluating remapped physical reach for hand interactions with passive haptics in virtual reality," *IEEE Transactions on Visualization and Computer Graphics*, 2018.

[20] V. Interrante, B. Ries, and L. Anderson, "Distance perception in immersive virtual environments, revisited," in *Virtual Reality Conference, 2006*, pp. 3–10, IEEE, 2006.

[21] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe, "Estimation of detection thresholds for redirected walking techniques," *IEEE Transactions on Visualization and Computer Graphics*, vol. 16, no. 1, pp. 17–27, 2010.

[22] R. Kopper, C. Stinson, and D. Bowman, "Towards an understanding of the effects of amplified head rotations," in *The 3rd IEEE VR Workshop on Perceptual Illusions in Virtual Environments*, vol. 2, 2011.

[23] E. Ebrahimi, S. V. Babu, C. C. Pagano, and S. Jörg, "An empirical evaluation of visuo-haptic feedback on physical reaching behaviors during 3d interaction in real and immersive virtual environments," *ACM Transactions on Applied Perception (TAP)*, vol. 13, no. 4, p. 19, 2016.

[24] L. Kohli, M. C. Whitton, and F. P. Brooks, "Redirected touching: The effect of warping space on task performance," in *3D User Interfaces (3DUI), 2012 IEEE Symposium on*, pp. 105–112, IEEE, 2012.

[25] H. G. Hoffman, "Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments," in *Virtual Reality Annual International Symposium, 1998. Proceedings., IEEE 1998*, pp. 59–63, IEEE, 1998.

[26] C. W. Borst and R. A. Volz, "Evaluation of a haptic mixed reality system for interactions with a virtual control panel," *Presence: Teleoperators and Virtual Environments*, vol. 14, no. 6, pp. 677–696, 2005.

[27] T. Mizuno, J. Maeda, and Y. Kume, "Weight sensation affected by vibrotactile stimulation with a handheld vision-tactile-force display device," in *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2013 10th International Conference on*, pp. 1–6, IEEE, 2013.

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

[29] L. Kohli, E. Burns, D. Miller, and H. Fuchs, "Combining passive haptics with redirected walking," in *Proceedings of the 2005 international conference on Augmented tele-existence*, pp. 253–254, ACM, 2005.

[30] M. Suhail, S. P. Sargunam, D. T. Han, and E. D. Ragan, "Redirected reach in virtual reality: Enabling natural hand interaction at multiple virtual locations with passive haptics," in *3D User Interfaces (3DUI), 2017 IEEE Symposium on*, pp. 245–246, IEEE, 2017.

[31] M. Suhail, S. P. Sargunam, D. T. Han, and E. D. Ragan, "Physical hand interaction for controlling multiple virtual objects in virtual reality," in *Proceedings of the 3rd International Workshop on Interactive and Spatial Computing*, pp. 64–74, ACM, 2018.

[32] T. C. Peck, H. Fuchs, and M. C. Whitton, "Evaluation of reorientation techniques and distractors for walking in large virtual environments," *IEEE Transactions on Visualization and Computer Graphics*, vol. 15, no. 3, pp. 383–394, 2009.

[33] "Unity 3D Asset Store: Viking Village." `https://www.assetstore.unity3d.com/en/#!/content/29140`. Accessed: 2016-11-22.

[34] V. Interrante, B. Ries, and L. Anderson, "Seven league boots: A new metaphor for augmented locomotion through moderately large scale immersive virtual environments," in *3D User Interfaces, 2007. 3DUI'07. IEEE Symposium on*, IEEE, 2007.

[35] S. Razzaque, Z. Kohn, and M. C. Whitton, "Redirected walking," in *Proceedings of EUROGRAPHICS*, vol. 9, pp. 105–106, Citeseer, 2001.

[36] D. A. Bowman, R. P. McMahan, and E. D. Ragan, "Questioning naturalism in 3d user interfaces," *Communications of the ACM*, vol. 55, no. 9, pp. 78–88, 2012.

[37] I. Poupyrev, M. Billinghurst, S. Weghorst, and T. Ichikawa, "The go-go interaction technique: non-linear mapping for direct manipulation in vr," in *Proceedings of the 9th annual ACM symposium on User interface software and technology*, pp. 79–80, ACM, 1996.

[38] E. D. Ragan, S. Scerbo, F. Bacim, and D. A. Bowman, "Amplified head rotation in virtual reality and the effects on 3D search, training transfer, and spatial orientation," *IEEE transactions on visualization and computer graphics*, vol. 23, no. 8, pp. 1880–1895, 2017.

[39] T. Feuchtner and J. Müeller, "Extending the body for interaction with reality," in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 5145–5157, ACM, 2017.

[40] B. Saket, A. Srinivasan, E. D. Ragan, and A. Endert, "Evaluating interactive graphical encodings for data visualization," *IEEE Transactions on Visualization and Computer Graphics*, 2017.