Physical Hand Interaction for Controlling Multiple Virtual Objects in Virtual Reality

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ABSTRACT

Immersive virtual reality systems often strive to support realistic physical interaction through direct hand control, but it is not often possible to configure the physical environment to exactly match the virtual environment. We study methods that allow physical hand interaction with virtual objects using passive props in scenarios analogous to home-use settings where a user might be seated at a desk or standing at a table. Our approach maps a single physical prop to multiple virtual objects distributed throughout a virtual environment. Leveraging prior work, we explore two adjusted travel techniques to facilitate physically aligning the user with the physical prop when ready to virtually interact with a virtual object: a redirection approach that uses rotational adjustments to gradually align the user during virtual locomotion, and the resetting approach that introduces a discrete rotational update when the user virtually approaches a target for interaction. Additionally, our work explores considerations for using one physical prop to control multiple types of object interactions. We report the results of a controlled study about usability of the two passive-haptic interaction methods as compared to a virtual hand approach without haptics.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Mixed / augmented reality**;

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1 INTRODUCTION

Often in virtual reality (VR), realistic interaction is a priority, where users would ideally be able to naturally use their real hands to directly interact with virtual objects while actually feeling the sensation of touching and moving the objects. Researchers have explored a variety of methods and devices for enabling haptic feedback during interaction [29]. One straightforward and effective alternative is to use *passive haptics*, which involves the use of simple physical props that correspond to virtual objects [12]. 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, Kohli et al. [16] investigated the combination of passive haptics with *redirected walking* techniques, which dynamically adjusts the user's virtual view while a user physically walks in a VR system in order to guide the user's physical travel in the real world [25]. Directing a user's physical movement can help align virtual and physical objects to allow realistic physical interaction [16]. Our research is motivated by the need for flexible techniques that 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 a convenient tabletop setups such as when a user is seated at a desk. For this reason, the research presented in this paper explores methods that allow physical hand interaction with passive props while the user remains at the same physical location.

Our research builds on prior work on passive haptics (e.g., [12, 16]), redirected touch (e.g., [1, 17]), and redirected walking (e.g., [25, 34]) to enable natural hand interaction with objects. Our methods allow for a single physical prop to be mapped to different virtual objects distributed throughout a virtual environment. To align virtual and physical objects while allowing free travel throughout a virtual environment, the research sits at the intersection between *travel and view control* and *selection and manipulation* tasks. While previous studies have evaluated the effects of semi-natural travel techniques on spatial orientation [26] and the effects of different configurations of reach performance with redirected hand control [10], our work combines these techniques in an immersive game environment. We note that this paper presents study results that

Figure 1: A screenshot from the game environment. An interaction zone is marked with a floating red marker.

extend previous preliminary findings discussed in a prior poster abstract [30].

We studied two approaches that enable passive-haptic interaction in situations with head-coupled rendering and virtual location: (i) a redirection approach that uses rotational adjustments to gradually align the user during virtual locomotion, and (ii) a resetting approach that introduces a discrete rotational update when the user virtually approaches a target for interaction. We demonstrate and evaluate our techniques in a VR game (see Figure 1) that uses of a single physical prop to control variable types of virtual interactions with different virtual objects. Because our work is heavily motivated by user preference and acceptance for interaction techniques, we conducted a controlled study to collect empirical data about the two techniques that support passive haptics, and we compared them to a standard virtual hand approach that lacks tactile interaction.

2 RELATED WORK

Our research combines concepts relating to passive haptics, redirected touch, and travel techniques in VR.

2.1 Passive Haptics and Tangible Interaction

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. [11] used a physical plastic doll head as a proxy for rotational control of 3D models. As another example, Meehan et al. [20] 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. [19] 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 [12] 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 [7, 8]. As another example, Kohli et al. [15] 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. [9] showed that visual feedback when accompanied with proprioceptive information can reinforce users' depth judgements to comfortably reach the hand to a physical target.

Following a similar approach, Azmandian et al. [1] proposed a framework for enabling reaching for props by warping the virtual body, virtual space and a hybrid technique that involves both. In this work, user's virtual hand position was shifted 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.

2.2 Navigation and Semi-Natural Travel in VR

The effectiveness of many VR travel techniques have been studied by researchers based on measures such as speed, accuracy, and effect on spatial awareness. Usoh et al. [31] found that the most natural and believable travel method in VR is physical walking where the user's movements in real world are tracked and the corresponding changes are applied to the virtual camera. For uninterrupted experiences, physical walking usually requires a large tracking space for the users to walk. Our research, however, focuses on more common setups and scenarios where more convenient interactions are expected or are required. More specifically, our research investigates techniques that would support interaction with props such as when seated at a table. In such cases, the user's physical position is typically constrained and virtual travel is usually controlled by less natural techniques such as *flying* (e.g., [5, 33]) or *teleportation* (e.g., [3, 4]).

Teleportation is a common travel technique used in most VR applications today where a user can instantaneously move from one point to another. In contrast, *steering* or *flying* techniques allow continuous movement. Though *teleportation* is better than *steering* in terms of speed and ease of use, *teleportation* can cause disorientation and doesn't allow users observe the environment while traveling since positional changes are discrete and instantaneous[5]. For virtual travel in the work presented in this paper, we use a widely used version of steering where the forward direction of a user's virtual travel is determined by the forward direction of user's virtual gaze but the direction of movement is controlled by the 2D directional input (such as an analog joystick) from a game controller.

Another consideration for travel and view control in VR is how to handle 360 viewing. With tracked HMDs, the virtual viewpoint usually matches the user's physical head orientation. However, in some cases, tracked head rotations can be modified before being applied to virtual camera to allow the users view larger segments of a 360 degree VE with smaller turns in real world. This approach, which we refer to as *head rotation amplification* has been studied in the past for various purposes [13, 23, 24].

Researchers have also studied the amount of rotational adjustment suitable or convenient for humans [24, 35]. For instance, Zhang et al. [35] studied human sensitivity to amplification levels that varied over the course of a physical turn. In other work, Ragan et al. [24] compared different levels of amplification and found that high levels of amplification with HMDs result in sickness problems.

2.3 Redirection and Reorientation

Redirected walking is a travel method used in VR to maximize the use of a limited tracking space to explore larger virtual environments with physical walking. The main objective of *redirected walking* is to redirect users away from physical bounds as they walk in real world. It was introduced by Razzaque et al. in 2001 [25] and has since been studied by many researchers. The techniques proposed by these researchers make use of perceptual illusion to achieve redirection. They exploit users' inability to notice minor rotational changes applied to virtual camera thereby making users to walk along curved path when they actually think they are walking straight towards certain targets in the VE.

In our previous work, we presented a version of redirected walking for seated scenarios using virtual travel [26]. Our technique, *guided head rotation*, applies minor rotational adjustments to the virtual camera to realign a seated VR user's head to a physical forward direction as they virtually move through a virtual environment using a game controller. We tested guided rotation method using amplified head rotations as a standalone technique for travel and navigation in VR. Study results indicated the general feasibility of using this technique without any training [26], though some participants experienced sickness. In the work presented in the current paper, we study the *guided rotation* approach in combination with passive-haptic interaction since our tabletop interaction scenario has a prop constrained to a limited physical area, and the *guided rotation* technique makes it possible to freely explore a virtual space without needing a 360 degree physical rotation.

A related concept is the use of washout filters used in motion simulators to move the simulation platform to simulate linear acceleration and angular banks [2]. The washout filters perform the required positional and rotational changes to the simulation platform while allowing the motion simulator to remain within its physical bounds [2, 32]. Once there's been a change in virtual acceleration, the physical changes are applied to the platform to simulate the corresponding vestibular sense. But these changes are gradually nullified and the platform is brought back to neutral orientation or close to neutral orientation over time.

Our research also incorporates *resetting*—another common technique that has been traditionally used to enable real-world walking. VR experiences that allow users to walk physically usually require the users to reorient themselves in the real world at some point during the experience to avoid colliding with physical objects or leaving the bounds of the tracked space For example, Williams et al. [34] studied variations of *resetting* techniques with real-world walking using HMDs, but they did not study resetting to enable physical object interactions or for experiences involving only physical rotation.

Even though the main objective of *redirected walking* techniques is to redirect users away from physical collisions, they are not successful all the time. There are cases where redirected techniques fail and users have to reorient themselves anyway with the help of reorientation techniques. Peck et al. [22] studied the use of visual distractors (e.g., a flying bird or floating object) to reorient users whenever physical bounds are reached. The researchers found that users preferred visual distractors over audio instructions for reorientation. Our research explores other methods for coordinating rotational adjustments, though we do provide explicit visual cues after resetting transitions in our study.

3 GOALS AND DESIGN RATIONALE

Our research is motivated by the desire to enable interaction with various virtual objects via passive haptics using a single physical prop. We focus on designs suitable for tabletop VR setups in practical home or office scenarios where physical space is limited and real walking is not ideal, but physical rotation is possible. The designs for our tested approaches were constrained to scenarios in which a physical prop is restricted to a limited range in a stationary physical space, such as when the prop is sitting on a table or desk (rather than more cumbersome or less practical scenarios that would require greater manipulation or configuration of the physical space).

Under these constraints, the primary challenge for flexible passive-haptic interaction is that allowing 360 degree exploration of a virtual environment through physical rotation, users might not always be properly aligned with the physical prop. Our research is guided by the following design goals:

1. **Multiple interaction locations:** Users should be able to interact with different virtual objects at different virtual locations. For practical scenarios and convenient setup, we aim to achieve this using a single physical prop.
2. **Multiple interaction types:** Passive haptics with a single prop should enable different types of interaction. Different transfer functions between physical and virtual interaction can allow tactile interaction for a variety of interactions.
3. **Flexible orientations:** Virtual interactive objects should be able to be oriented at any orientation in the virtual world. Ideally, designers should not have to configure the virtual world to match the physical world.
4. **Freedom of choice:** Users should be able to choose which objects to interact with. When interacting with multiple objects at different locations, the order of travel and interaction should not be pre-scripted or controlled.

4 TECHNIQUES

We explore and combine multiple techniques that meet the above design constraints while enabling interaction with multiple virtual objects using passive haptics with a single prop. Under the previously described design constraints, our techniques only allow virtual translational travel (in the presented work, we used a game controller for translational movement), but we consider different approaches for rotational control and coordinating interaction with a physical prop. Our research considers two techniques for aligning the user's body orientation towards a given physical forward

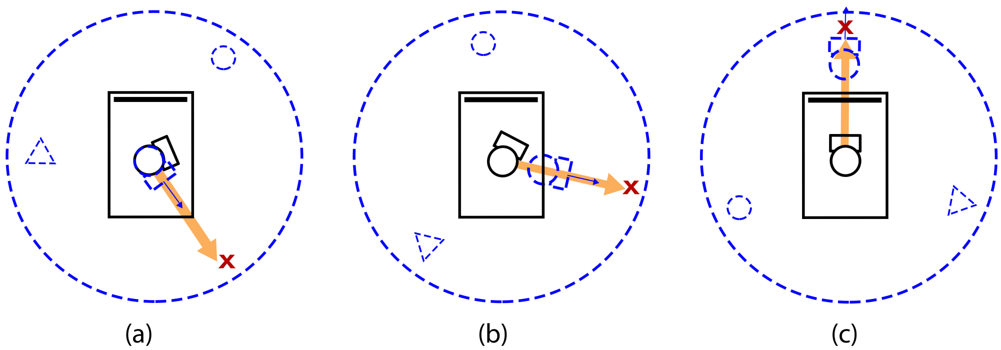

Figure 2: Top-down diagram showing realignment via rotational gains for guided rotation. Rotational gains are applied during virtual locomotion. The black content represents the physical world and user, and the blue content represents the virtual world and user. The orange arrow shows the virtual path of travel progressing through three stages (in order: a, b, and c). By gradually rotating the virtual world as the user travels along the virtual path (orange arrow), the user is encouraged to rotate with the virtual rotation and ultimately faces the real-world forward direction.

direction (i.e., the direction with physical prop): *resetting* and *seated redirection*. Additionally, we incorporate *redirected reach* to help match the physical and virtual hand in such a way that to facilitate hand interaction with the prop.

4.1 Resetting

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., [22, 34]). Our implementation uses 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 and the transition took one second. The resetting transition triggers when the user moves near an interactive virtual object—we call these areas *interaction zones*.

After the transition, the virtual orientation has been changed, but physically turning to face the virtual object will physically align the user with the physical prop. As an additional rectification step, along with the virtual world rotation, the *resetting* technique also changes the position of virtual camera along the horizontal axes. The position is updated in such a way that the virtual camera is positioned right in front of the horizontal center of the virtual interaction zone. Because a user might enter the cubical interaction zones from any direction and the virtual and physical interaction zones might not always be positioned similarly from user's real world perspective and virtual camera's perspective. Thus, this positional adjustment approximately matches the real world interaction zone and virtual world interaction making the passive-haptic interaction more believable.

To help users understand the resetting transition, our technique displays an arrow to denote the shortest direction of physical turning required to face interactive object. The arrow is hidden once the user turns close to the intended direction.

4.2 Guided Rotation

Guided rotation is a composite travel technique used to align the virtual and physical coordinate systems to enable passive-haptic interaction with a physical prop. Our implementation combines two elements: *realignment via rotational gains* and *amplified head rotations*. The effects of these techniques on spatial orientation and sickness have been studied in [26].

4.2.1 Realignment via rotational gains. The goal of *guided rotation* is to redirect the user's physical orientation towards a known default forward direction—in our case, the direction of a table with the physical prop. We used a redirection method to gradually adjust the orientation of the virtual world as the user virtually moves towards a virtual interaction zone. As a result, the user is encouraged to physically rotate in the opposite direction to maintain alignment with the target direction. This is the same fundamental approach of applying rotational gains during real walking for redirected walking techniques [25, 27], except in this case, virtual locomotion is used instead of real walking. The result is the same; to keep the virtual target consistently centered in the virtual view, the user physically rotates towards a given direction. In our case, users physically rotate to eventually align with the physical prop.

The main difference between pure *resetting* and *guided rotation* is the way that rotational changes are applied to the viewpoint. With *resetting* alone, the rotational change is applied instantaneously, which may result in a large change depending on the physical orientation at the time of the transition. In *guided rotation*, the rotational updates are applied gradually over time.

To determine the direction and value of rotational adjustment during virtual travel, our implementation of the realignment technique determines the virtual destination from a list of known target destinations. In this study, the targets correspond to the interaction zones. During virtual travel, the closest interaction zone in the travel direction is chosen as the intended target.

Once the target is predicted, the value of rotational adjustment is calculated based on the user's virtual distance from the target. The adjustments always start from a value of zero as the user starts moving towards the target and it gradually increases to a maximum value so users do not experience disorientation due to sudden rotation changes in the virtual camera. The rotational adjustments reaches the highest possible value at the midpoint between the virtual position from where the user started moving and the virtual target. After this midpoint, the technique gradually reduces the rotational adjustments to zero as the user moves closer to the target destination. Our implementation used a Catmull-Rom spline to ease the interpolation in an attempt to reduce discomfort, and highest rate of rotational adjustment rate was 10.8 degrees per second.

4.2.2 Amplified Head Rotation. One problem with using rotational realignment via rotational gains in any virtual environment is the rotational gains could be large if the mismatch between physical orientation and virtual target destination is large. To compensate for this problem, we explored the use of *amplified head rotations* to enable 360 degree viewing of virtual world with lesser physical turns. Amplified head rotations are used in our research to meet two objectives: 1) to limit the user's real-world head orientation to within 90 degrees of the forward direction of the physical interaction area, and 2) to enable 360 degree virtual viewing without the need to physically turn large amounts in the real world.

To achieve amplified head rotation, the ratio of virtual rotations applied to the camera from the user's physical head rotations are adjusted according to an amplification factor [28]. A common practice is to amplify head rotations with a constant amplification factor [21, 24]. However, head rotations can also be amplified with dynamic amplification factors [18, 35]. Our technique used a dynamic factor to suit the passive-haptic interaction with the physical prop; that is, we wanted minimal amplification when users would be facing forward (towards the prop), but the amplification still needed to increase to allow 360 viewing when turning away from the prop.

The amplification factor was calculated dynamically using a cosine function that operates on the difference in heading in real-world head rotation from the head rotation corresponding to the given physical forward direction.

The formula we used to calculate the amplification factor is $a = (1 - cos(h)) * c + 1$, where a is the amplification factor, h is the difference in heading between tracked HMD rotation and the neutral forward direction, and c is constant maximum gain added to default amplification factor of 1. In our previous work [26], we chose a value of 2.5 for c since *guided rotation* was tested using a non-swivel chair and high amplification levels were needed towards the extreme real world head orientations to view most of the virtual world. After participants reported sickness problems associated with *guided rotation* [26], we decided to reduce the value of c to 2 for the implementation in this study. To account for this reduction in amplification levels, participants used a swivel chair with *guided rotation* since the focus of this research was tabletop passive-haptic interactions and not necessarily for stationary seated conditions. The calculated amplification factor reaches a maximum value of 3 when the heading difference (h) reaches 90 degrees on either side of the neutral forward direction and it reaches the least possible value of 1 when the heading difference (h) is close to zero. Thus, a user would be able to see more of the virtual world as she rotates further towards both ends of horizontal periphery in a seated position whereas the rotational changes are close to real world tracked rotations when user's real world head orientation is close to physical forward direction.

The *guided rotation* technique focuses on rotational adjustments that could be comfortable for usage rather than perfectly and completely realigning the users with their physical forward directions. As a result, even after rotational adjustments are applied during travel, the user's head could still be offset from the physical forward direction when virtual interaction zone is reached. To address this, the *guided rotation* technique also uses a *resetting* transition as discussed in section 4.1. However, while *resetting* used with standard 360 degree rotation can have large rotational updates (up to 180 degrees), the resetting updates are significantly smaller in guided rotation since most of the realignment is already achieved gradually during virtual travel. The specific resetting rotation depends on the distance between travel destinations, but in our game environment, rotational updates were less than 30 degrees.

4.3 Redirected Reach

While the *resetting* and *guided rotation* techniques help physically align the user's reference frame with the prop for interaction, issues can remain due to movement of the prop during a virtual experience, and the position of physical prop will 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. In a previous interaction, the physical prop can easily be placed out of reach, or at least positioned at an uncomfortable distance away from the user.

To account for any remaining 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. The virtual hand is shown as a floating object without a virtual arm or attachment to a virtual body.

Additionally, to limit the offset between physical and virtual objects, we linked updates of virtual object movements in a way that takes advantage of perceptual inattention to environmental changes (i.e., change blindness). Where the movement of one virtual object in one interaction zone affected all the virtual object movement. This way, the differences between physical and virtual object positions are reduced to prevent the physical prop from moving to an uncomfortable or inconvenient position. This prevents situations where a user would have to move the prop off of the table or extend the object further than arm's reach.

5 EVALUATION

We conducted a controlled experiment to evaluate two methods that support passive-haptic interaction methods as compared to a virtual hand approach without haptics.

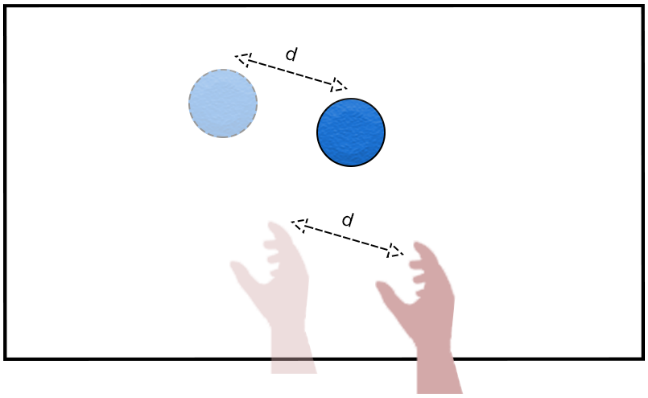

Figure 3: A top-down diagram demonstrating *redirected reach* shows the real world table in black. The virtual hand and virtual object are shown in faded colors. d denotes the vector offset between the virtual and physical objects.

5.1 Game Environment

To test our techniques, we designed an immersive game environment (see Figure 1) 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 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).

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 5). With this design, different interaction zones had different virtual orientations when compared with the physical world, so users had to physically rotate to orient themselves with the physical prop.

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 1).

5.2 Experimental Design

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

- **Resetting:** 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.
- **Guided rotation:** This condition included interaction with the passive haptic prop. Rotational viewing was controlled via amplified head rotation with redirected rotational adjustment during virtual locomotion. Resetting transitions were also applied when entering interaction zones. Redirected reach was applied to adjust the virtual hand.
- **Air grasping:** 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. Redirected reach was not applied.

The experiment followed a repeated-measures design, so each participant experienced three game trials—one for each of the three conditions. For ordering of conditions, we were concerned about sickness effects due to the rotational manipulations in the *redirection* condition, as prior studies found that some people get sick using such techniques [26]. While we realize the limitation in the experimental design, this technique was the most complex of those tested, and we did not want any negative effects to transfer to the other conditions. Consequently, participants always experienced the *redirection* condition as the last of the three. 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 collected measures about sickness effects using both the Simulator Sickness Questionnaire (SSQ) [14] and relative ratings of techniques on a 1–10 scale. 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.

5.3 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.

The experiments were conducted in a lab using a Oculus Rift CV1 HMD. Head-tracked viewing (positional and rotational) was enabled using the Oculus Constellation tracker, though position head movements were limited because participants were seated. Participants were seated in a swivel chair in front of a table holding the physical interaction prop—a plastic water bottle with weights inside for added stability at the base.

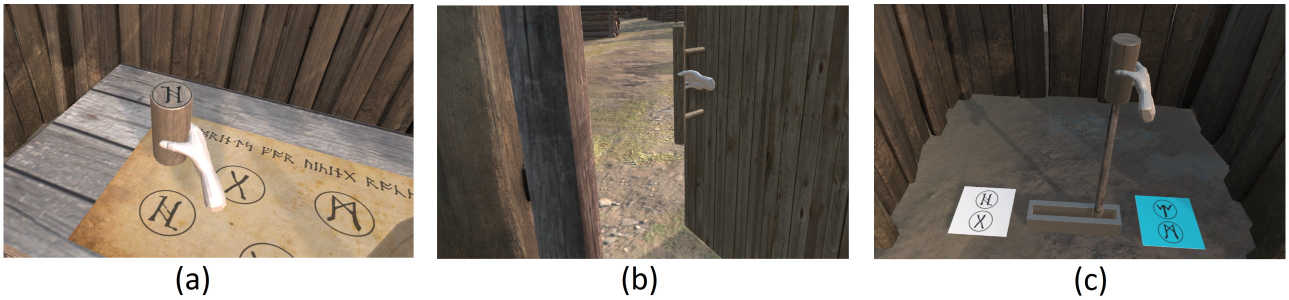

Figure 4: Three different types of interactions in the game: (a) Moving a puzzle piece during symbol matching, (b) opening a door, and (c) operating a switch.

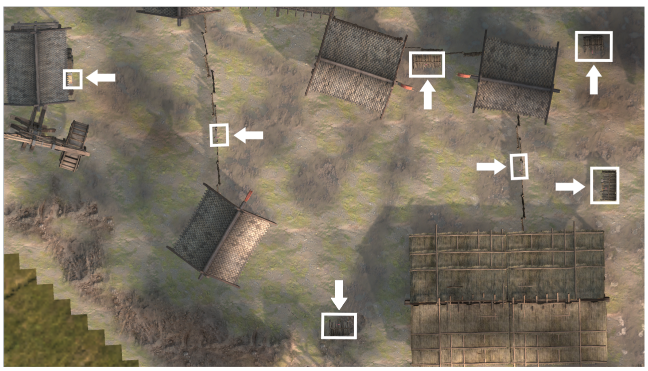

Figure 5: Top-down view of the virtual world with interaction zones represented by white rectangles. Arrows denote the expected direction of user approach.

To track the prop and the player's hand, the setup used an Optitrack capture system with eight Flex 13 cameras. Both the physical prop and user's hand were tracked using Optitrack trackers.

A wireless Xbox game controller was used for controlling virtual movement and the game-menu inputs.

5.4 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) and their self-reported experience with 3D games and VR. Next, participants completed an initial simulation sickness questionnaire (SSQ; from Kennedy et al. [14]) as a baseline for the subsequent sickness questionnaires after using the techniques. Before putting on the HMD and the markers on the hand, the participant was given an explanation of the controls for navigation, in-game instructions.

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 air grasping and physical prop techniques. 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, participant were asked to complete the entire game three 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 each trial, participants were given another break and asked to complete two questionnaires: the SSQ [14] and a system usability scale questionnaire (SUS) [6]. The SSQ was used to evaluate any fatigue or sickness experienced after completion of each trial, and the SUS allowed the participant to give usability feedback on the game experience and techniques used.

For the third and final trial, participants were given an overview of the guided rotation technique specifically to explain that they would be experiencing amplified head rotations and realignment when traveling. Unlike the two previous versions of the game the participant had experienced, the guided rotation technique does not require users to use the complete 360 degree rotation within their chair, so participants were advised on how to use the technique properly and what to expect to avoid any surprises with the changes in world rotations.

After all three 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, sickness, and overall experience. Finally, a semi-structured interview was conducted by the experimenter to collect additional feedback.

5.5 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. All participants were university students in various 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.

6 RESULTS

We were interested in understanding user preference and experience while testing for natural hand interactions in a table-top VR experience. We do not report the results of traditional inferential statistical analyses because we did not detect significant quantitative differences among the techniques. However, it is important to note that this was not of primary interest. We know that the tested techniques can work and have different advantages and disadvantages for interaction, but it is important to understand user preferences and frustrations for the different components of the different techniques. For this reason, we focus on subjective responses and qualitative feedback about the techniques. The following results are based on the data collected from the user study via standard questionnaires and post-study interviews. We report the following information on sickness, system usability, and user experience.

6.1 Sickness Results

For sickness results, the SSQ [14] questionnaire provides responses based on nausea, oculomotor discomfort, and disorientation. As none of these individual subcategories was particularly high, we only report the total SSQ severity score combining all three subcategory scores. Figure 6 shows the distribution of the total SSQ scores for the three conditions. The box-and-whisker plots show quartiles and outliers for the sickness scores, which range from 0 to 235.62. Note that all reported sickness scores are relatively low overall, though average scores are higher for *guided rotation* (M = 69.19, SD = 2.64) as compared to *resetting* (M = 13.09, SD = 18.51). This is not unexpected, as prior studies have found that rotational manipulations can have negative sickness effects (e.g., [24, 26]). The non-haptic technique, air grasping, had overall sickness scores of M = 31.79 and SD = 7.93. Differences were not statistically significant.

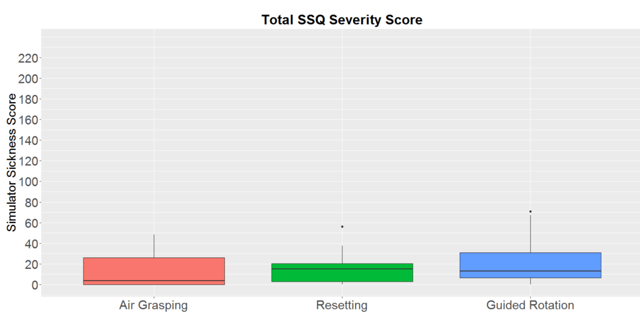

Figure 6: Total SSQ severity scores are relatively low for all techniques.

6.2 Usability and Preferences Results

We used questionnaires to get feedback about overall usability of the various conditions. Participants completed an SUS usability questionnaire [6] after each trial to provide a measure of subjective usability considering system effectiveness, efficiency, and satisfaction. This results show that all techniques have similarly high overall usability scores, with scores ranging from 60 to 82.5.

We also collected ratings from a post-study experience questionnaire based on how much fun each technique was, how easy the controls were, and how disruptive or distracting the interactions were. We were particularly interested in user perception of disruption and distraction for the passive-haptic configurations, as resetting causes a clear break in the experience, and the guided rotation could influence user control during free exploration. Figure 7 shows the results for the distraction ratings for the three conditions. As expected, some participant did find that the resetting and guided rotation techniques disrupted the experience, but we were surprised to find that most ratings were relatively low for all techniques. Statistical testing found no significant differences.

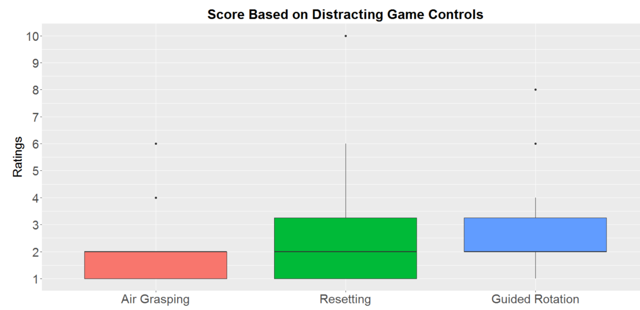

Figure 7: Techniques rated based on disruption and distraction from the game experience.

6.3 Qualitative Results

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.

6.3.1 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."

6.3.2 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. While not necessarily 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."

6.3.3 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."

6.3.4 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."

6.3.5 Feedback about Guided Rotation. The guided rotation technique combined amplified head rotations and realignment via rotational gains. In terms of user experience, participants commented on both components. Four participants mentioned that the amplified head rotations were helpful in quickly exploring the game environment. These participants adjusted quickly to the technique and reported that they hardly noticed a difference in comparison to standard 360 degree rotation.

Recall that we explicitly explained the amplification and rotational adjustments to participants before they completed the guided rotation trial. Five participants preferred using guided rotation. These participants commented that they thought the rotational gains were slow enough to not cause disorientation. Regarding the overall experience, 10 participants commented that using guided rotation was difficult due to reduced control in exploring the virtual environment. Additionally, those participants reported symptoms of dizziness and disorientation after this trial. A few representative quotes on guided redirection include:

> "I felt like redirection was forcing me to go a certain way, but I prefer having full control."
> "I prefer the quicker turns. And I didn't get dizzy."
> "I didn't feel much difference from other versions in term of experience except the learning curve involved."

7 DISCUSSION AND FUTURE WORK

In our work, we demonstrate two approaches for enabling passive-haptic interaction on a practical tabletop setup using one physical prop for interactions with multiple objects distributed at different locations. We also demonstrate use of a single prop to control different types of interactions using different transfer functions to preserve moderately high levels of interaction fidelity for each interaction. Overall, our results demonstrate that both the guided rotation and resetting approaches were successful and usable in a game environment allowing free exploration and choice of interactions, though different participants had varied preferences and reactions about the different techniques. When tested for overall user preference between air grasping, resetting, and guided rotation techniques, results from system usability scores and post-study experience questionnaire did not show a single technique that was equally preferred by all participants.

The *resetting* condition applied large discrete rotational changes at interaction zones in comparison to the *guided rotation* technique, where the rotation changes are gradual and continuous along the path. From our results and experience in designing adjusted travel techniques, we could say lower rotational changes at the interaction zone helps the user to stay engaged and not get disoriented or distracted from the current task. Generally, many participants were interested in interacting with a physical prop, and the responses from participants indicate that they could keep track of their physical orientation in the real world using a stationary physical prop.

Participants reported a higher sense of control and realism while interacting with a physical prop as compared to the air grasping without tactile feedback. Additionally, our results show participants had preferences of different types of interactions. Freely moving and placing the puzzle objects in 6DOF to specified targets was the favorite interaction as it followed a direct mapping to the real world task performed. In contrast, they felt that opening doors did not work as well since there was a learning curve involved in how the physical object should be moved, and the prop control did not directly match the real-world interaction of opening a door.

While the methods studied in in this paper show promise, they are not without limitation. With our current approaches using *redirected reach*, users could only interact with one virtual object in a given virtual location. In future work, we want to explore the possibility of having multiple virtual targets at the same location and apply prediction for target selection for reaching different objects based on gaze and movement of the virtual hand.

Also, our work use a basic cylindrical object as a proxy for multiple virtual objects having a similar cylindrical form factor (i.e., handles and cylindrical puzzle objects). While the sizes of the virtual objects were not accurate compared to the physical prop, no users commented on noticing these differences in scale and size. Exploring usage of different 3D shapes as primitives for physical props can be an interesting area of research for future work.

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