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Determining Detection Thresholds for Fixed Positional Offsets for Virtual Hand Remapping in Virtual Reality

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ABSTRACT

Virtual reality commonly makes use of tracked hand interactions for user input. Interaction techniques sometimes alter the mapping between the real and virtual coordinate systems to modify interaction possibilities. This paper studies fixed positional offsets applied to the location of the virtual hand. We present a controlled experiment in which users' hands were subject to fixed positional offsets of varying magnitudes while completing target-touching tasks. The study provides estimations for detection thresholds for positional hand offsets in six directions relative to the real-world location of the hand and provides evidence performance using offset virtual hands can vary based on offset parameters. Significant differences in offset detection were identified based on offset direction, indicating that positional adjustments made to virtual hands should consider directionality when limiting techniques rather than just a constant value. Hand offsets kept within the threshold value resulted in comparable performance to unmodified hand registration, while offsets beyond the threshold resulted in larger completion times.

Index Terms: Human-centered computing—Human computer interaction—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction—Interaction techniques

1 INTRODUCTION

The use of hands as the primary means of interacting with the virtual world in virtual reality (VR) systems is important for developing usable applications. They commonly are used for aiming, pointing, interacting with objects in the scene, and providing input via controllers. While motion capture and hand tracking systems becoming more widespread, controllers are still most used in consumer-level VR headsets (e.g,. Oculus Rift, HTC Vive, Valve Index).

The physical limitations that come with a user's fixed arm length, even when using controllers, is one issue that comes with hand use in VR. A player can only influence an area that is within reach, which reduces interaction capabilities in large scenes. *Hand remapping* techniques to enable further reach or increased movement have been explored to provide a wider range of interactions by moving the virtual hand to a location that differs from its real-world location. For example, moving the user's virtual hand a larger distance than their real hand moves based on how far their arm is extended [31]. Remapped hands can also be used to facilitate the use of haptic props, or physical objects used to simulate the feeling of grasping or touching virtual objects (i.e., [1, 6, 17]).

Despite their use in providing users the ability to interact with more features of a scene, these remapped hand techniques, if applied at a large enough magnitude, can become noticeable and distracting to users. Maintaining natural and undetectable hand placements can increase user immersion and help create more realistic interactions. Several types of hand remappings have been able to be applied without users noticing them. These include rotations along a specific axis [15, 40], gain-based warping [40], and scaled movement [11]. It is possible to estimate a set of *detection thresholds* (magnitudes to which a technique can be applied before they are detectable to users) which can guide the use of these techniques if natural feeling techniques are desired.

Hands can also be remapped by applying a fixed offset to the hand. In these types of transformation, the location of the virtual hand is moved a constant amount regardless of hand movement. Prior work has examined selection and navigation using these types of transformations [26, 27] with a focus on user performance rather than detection. Additionally, these types of offsets may be introduced accidentally by poor tracking systems. This necessitates further research into detection thresholds for constant hand offsets in each direction in addition to understanding how offset direction and magnitude affect target selection and performance.

Henceforth, our research focuses on answering the following questions:

- **Q1:** What are the maximum constant offsets that can be applied to a user's virtual hand in each direction before it is perceptibly not normal, and how do they differ from one another?
- **Q2:** How do offset direction and magnitude affect target selection?

We seek to determine detection thresholds in less restrictive scenarios as opposed to the highly controlled movements examined in previous work [15, 40]. Previous studies propose highly conservative thresholds for other techniques which may be stricter and less generalizable than those that may be observed during free user movements. Therefore, we designed and conducted a psychophysical experiment utilizing a two-alternative forced-choice methodology to test user perception of constant hand offsets and estimate detection thresholds using psychometric functions. Participants were repeatedly asked to touch a series of targets placed in front of them as quickly as possible while offsets of varying magnitudes and directions were applied between each instance of the task. After each task, participants reported if their hand placement was normal or not normal and these responses were used to determine our detection thresholds. Results show significant differences in detection thresholds for offsets in each direction, and found that hand offsets within the threshold produce comparable performance to unmodified, normal hands.

2 RELATED WORK

Our work builds off prior work investigating remapped hand interaction techniques and human detection of these techniques. We examined what is already known about how these techniques impact performance, and identify areas where further exploration is warranted.

2.1 Remapped Interaction Techniques

Many types of interactions in VR are limited by the physical capabilities of users or the space being utilized. For example, if VR

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applications solely use the real-world positioning the user or other tracked objects in a scene then users are limited by the size of their room in how much they can walk in a scene or the length of their arm in reaching for objects. Prior work has examined remapping techniques for walking and travel [19, 33, 37, 38], head rotations [34, 36], and hand positioning [1, 6, 29] in order to increase user abilities in VR.

In order to allow users to walk and navigate through large virtual spaces when physical space is limited, Razzaque et al. [32] proposed *redirected walking*. Rotations are applied slowly as users approach a physical limit to unknowingly adjust the user's physical movements. They also examined rotations of the virtual scene in a CAVE [7] system to redirect a user's positioning [33]. Their goal was to prevent users from seeing the missing wall that is present in CAVE systems, however no significant time facing the backwards direction was found. This provided a strong foundation for later work by later researchers that explore walking and travel manipulations. In order to increase travel distance, Interrante et al [19] proposed the *Seven League Boots* method of increasing travel in VR. In their technique, travel is amplified based on user gaze direction (assumed to be pointing in their desired direction of travel) and their movement direction in order to minimize rapid movements based on natural head movements during walking. Vertical head movement is ignored in order to prevent natural head bobbing while walking from increasing or decreasing the user's height substantially. This technique has shown to provide significant qualitative benefits over regular walking. To compare two important features of movement (rotation and translation) Steinicke et al. [37, 38] investigated the use and detection of both in *redirected walking*. Users were found to be more sensitive to rotations than increased or decreased translational movement. These rotations can be applied to redirect a user into walking a circle of radius 22 meters before redirection is detected. When user movement speed was modified, the distance walked in VR can be increased by 26% or decreased by 14% before it is noticeable to users. Grechkin et al. [16] examined the combined use of rotational and translational gains in redirected walking. While translational gains did not affect detection of rotational gains, a different methodology suggests that walking in circles of radius 11.6 or 6.4 meters may be undetectable to users.

Rotations of the user's head have also been leveraged to enable seated travel in VR. Sargunam et al. [34] propose *guided rotation*, a technique which rotations are introduced to the user's view in order to bring their field-of-view towards a known area of interest. By interpolating the amount of rotation based on angular distance between the user's current and target field-of-view, users experience changing speeds of head rotation. Overall the method worked as intended to better enable semi-natural travel despite negative impacts on other factors. Later, Stebbins et al. [36] furthered this work by adding activation thresholds. Rather than constantly rotating the user's head, rotations are only applied if the user's head is rotated away from normal by a chose value for an extended period of time. Fast and slow rotations were also examined in conjunction with different rotation thresholds and activation times. Slow rotations of the head were less noticeable to users, but also did not reduce head rotation from the forward direction as much as quicker rotations. Overall, a threshold of 45 degrees with an activation time of 2-4 seconds and a speed of 3 degrees per second was recommended.

Most related to our research are techniques that manipulate hand positioning in VR. Many hand remapping techniques have been previously explored as a means to influence user interactions and perception in VR. Poupryev et al. explored the use of arm extension in the Go-Go technique [31], where a user's hand extend further away from them as their arm stretches out from their body. This enables users to effectively reach further into a scene than their natural arm reach would allow them to. Later, Dominjon et al. [8] formalized techniques such as this as modifications to the Control/Display (C/D) ratio, or the ratio between real motion and displayed motion. They found that C/D ratios smaller than 1 (i.e., user movements were amplified) created sensations of objects being lighter than reality while C/D ratios larger than 1 increased the perceived weights of objects. Decreased C/D ratios were later examined by Frees and Kessler [13] as a means to provide more precise movements as apposed to increased movements like Go-Go.

Humans have been shown to have an altered perception of space and depth in VR compared to the real-world when reaching and moving their hands [10]. Despite this prior work has been able to leverage hand movements to produce a variety of interaction techniques in VR. Kohli first proposed leveraging visual dominance in a haptic context and describe issues, such as mistraining in learning contexts, that may arise from improper use of input remapping [23]. Azmandian et al. [1] provide evidence for the use of remapped hands to facilitate passive haptics (physical props) in VR. In their *body warp* and *hybrid warp* techniques, the displayed virtual hand is moved in order to retarget a user's hand towards a physical object representing a virtual object in the scene as they try to grab it. This allows the physical and virtual locations of objects to differ which allows more complex scenes. They also propose *world warp*, in which the virtual world is moved in order to match the target's virtual location with a physical prop. Kohli et al. have investigated user performance under world warping techniques, and have demonstrated similar user performance to unwarped virtual space [24] and that users can adjust to using the technique over time [25].

Trade-offs exist between different hand redirection techniques. Han et al. [17] examined two different techniques: translational and interpolative reaching. In the former, the virtual hand is offset based on the distance between a virtual prop and its real-world location. While the user is not holding the prop, their hand is displaced a constant amount along the horizontal plane based on the distance between the virtual and real prop. In interpolative reaching, the user's virtual hand is gradually adjusted toward the virtual target while the user corrects their movement towards the real target. Analysis of task times shows that increased offsets lead to larger times as users need to adjust their movement. Overall, users preferred translational reaching which also had better performance measures.

Retargeting has also been applied to scenarios besides grabbing objects. Cheng et al. [6] utilized hand retargeting in conjunction with a *sparse haptic proxy* in the form of a hemispherical wall placed in front of the user to simulate surface orientation. As the use extends their arm, they are redirected towards a section of the wall that matches the orientation of the virtual surface they are attempting to touch. Matthews et al. [29] leveraged hand targeting to allow a single physical button on a controller to represent several virtual buttons by warping the interface as the user's hand approaches a button. This enables users to have a wider degree of interactions available to them via buttons.

It is important to understand how performance is affected by remapped hands, as movement is often increased or hands offset from their real position. Li et al. [27] compared the effects of four different hand mappings (no offset, fixed offset, linear offset, and Go-Go) on task performance in a Fitts' Law multidimensional tapping task following the ISO 9241-9 standard. They determined that no offset is more efficient while the target is in reach, but that linear offsets (where the virtual hand is moved proportional to the distance between the user's head and real hand) outperforms no offset, fixed offsets, and Go-Go for targets out of reach. Performance using fixed offsets did increase as target distance increased. However, this work only examined fixed offsets in one direction (away from users). Prior to this, they examined the use of different hand remapping techniques (no offset, fixed offset, linear offset, and non-linear offset) in navigation using CAVE systems [26]. Longer offsets were found to be most beneficial to task performance. However, given the context of use this is not necessarily applicable to object touching or grabbing tasks where targets are close to the user. In both studies, no investigation into detection was conducted which also leaves questions about absolute magnitudes of undetectable fixed offsets and impacts on task performance.

More recently, Wentzel et al. [39] have examined non-linear transfer functions when remapping user hand movements. Hand movement is scaled a larger amount while the hand is near the user's body, and gains are lessened as the user extends their arm. Ten different levels of their technique were evaluated, ranging from a linear hand mapping to a function that moves the user's hand 45% beyond their arm length. Higher amplifications tended to result in comparable or better performance and comfort and less physical movement by users. Detection of each amplification level was also informally examined with 61% of participants detecting the technique by the fifth level (maximum offset of 25% beyond the user's arm length).

2.2 Detection of Remapped Hands

The introduction of modified interaction techniques comes with trade offs between increased user agency and "natural" interactions. Of interest to us is if these techniques feel *normal* to users (i.e., if users feel their remapped hand still feels regular). Prior work has proposed detection thresholds for different remapping techniques.

Burns et al. examined the use of hand remapping to avoid visual interpenetration between user hands and objects in a virtual scene [4]. They propose detection thresholds for visual interpenetration and sensory discrepancies but we were unable to determine significant differences for specific directions of differences Their findings show that humans are more sensitive to visual interpenetration than the proprioceptive differences between their real hand location and the displayed position. Burns et al. also demonstrated that users are more sensitive to decreases in hand speed compared to increases [3] and applied this knowledge to create more natural hand placements when hands collide with objects in a scene [5].

Zenner and Kruger have proposed detection thresholds for vertical warp, horizontal warp, and gain warp techniques to user hands in a single target-touching task [40]. In vertical and horizontal warp, the user's hand is rotated around a calibrated pivot point by an angle α whereas gain based warping scales the position of the hand away from the pivot by a specific gain factor. It is estimated that under the influence of these techniques, hands can be redirected up to 4.5° in either direction vertically or horizontally, scaled up by a factor of 1.07 or scaled down by a factor of 0.88 in gain based warping. Similarly, Gonzalez et al. [15] examined the use of bimanual haptic retargeting using rotational offsets about the user's shoulder. Single hand, bimanual same-direction, and bimanual opposite-direction rotations to hands were examined. Offsets in the opposite directions yielded lower detection thresholds and offsets in the same direction produced higher detection thresholds. When examining the movement of hands, Esmaeili et al. [11] have provided limits for scaled hand movements both in isolated directions and all three directions at once. Significant differences were identified between scaled movements in each direction for movements along the X, Y, and Z axes indicating thar humans have differing sensitivity based on the axis of movement. This prior work all provide evidence to suggest that *direction* plays an important role in detection, as detection thresholds were found to vary between axes or directions. It stands to reason that thresholds for offsets will also vary based on direction.

It has also been demonstrated that other factors in conjunction with remapping techniques can affect detection. Ogawa et al. [30] investigated the effects of hand representation (realistic and abstract) on detection of angular hand remapping to the left and right. Using realistic avatar representation decreased sensitivity to displacements relative to the body midpoint by as much as 31.3%, with a maximum threshold being 4.5cm from the body midpoint. These findings suggest that higher fidelity avatars relative to the user's body allow for decreased detection of remapped hands, perhaps because users are not as focused on hand placement since it matches their own body.

In studies designed to determine detection thresholds for different types of stimuli (i.e., detecting left/right rotations [30,40]), psychophysical methods are used. Two-alternative forced-choice (2AFC) is a type of psychophysical method in which uses must respond with one of two options (i.e., left or right) given a specific magnitude of a stimulus (i.e., amount of rotation applied to the hand) [14,21]. By varying the stimulus over many trials, estimations for detection thresholds can be determined. These methodologies have been widely utilized not just for remapped hands [11,15,30,40], but for other remapping techniques as well (i.e., [2,16,18]).

While previous researchers have proposed detection thresholds for rotational, gain-based offsets, and scaled movements, prior work has not focused on maximum *positional* offsets that can be applied to hands for each direction. Constant positional offsets differ from prior techniques investigated since they are constant regardless of the movement of the user's hand. Prior work has also largely focused on determining conservative thresholds for very specific movements rather than general movements which provides only a lower bound for these thresholds [15,30,40]. It is important to identify detection thresholds for these offsets in a realistic scenario to better understand the absolute distances hands can be moved before they are detectable, rather than detection using a specific technique.

Although not the focus of our research, it is important to note than remapped hands can hinder immersion in multiple ways. One such way is by decreasing user *ownership* over the hand displayed (i.e., the degree to which the hand feels like a real part of the user's body). While techniques such as Go-Go [31] may allow users to reach across a room, such interactions may not feel normal if hands are moved too far from the user's body. Feuchtner et al. [12] have demonstrated that ownership of a virtual hand using Go-Go is impacted by how the hand is connected to the user's virtual body. Displaying a single stretched arm, rather than a realistic floating hand, abstract floating hand, or simultaneous view of the real and stretched arm produced higher ratings for body ownership. This indicates that continuity and connectedness in an avatar are important in body ownership when user body parts are not displayed in their real location.

Overall, there has been a lack of focus on detection for constant offsets applied to hands. Continuous techniques that modify offsets as they are used (i.e., scaled movement) typically do not examine the actual distance hands are moved when they are applied to the largest extent. Additionally, performance of uni-directional offsets has on;y been considered without much attention to the size of offsets and along only one axis [27]. The robustness of constant offsets in two directions (i.e., hand retargeting via translational reaching [17]) in usability tests necessitates further understanding of their perception by users. Our work addresses both of these issues by providing detection thresholds for constant offsets and examines the effects of direction and magnitude on target selection.

3 EXPERIMENT

Our experiment is designed to determine detection thresholds for fixed offsets in six directions and determine how they impact user ability to utilize their hand. Offsets of varying magnitudes are applied in each direction while users touch a series of targets. Then users respond if their hand feels normal or not. These responses as well as their time to complete each trial allow us to determine the detectability and performance effects of each hand offset.

3.1 Goals and Hypotheses

Our primary goal in this experiment was to determine detection thresholds for fixed offset hand placements in VR applications that use a wide range of hand movements. To do this, we chose a multiple target touching task as the activity for our study. We also seek to identify how offset magnitude and direction affect user ability to touch targets effectively with their hand. Based on these design choices and our research questions, our hypotheses are as follows:

- **H1**: Detection thresholds will significantly differ between directions.
- **H2**: Offset *direction* will significantly affect target selection time.
- **H3**: Offset *magnitude* will significantly affect target selection time.

3.2 Design

Our experiment examined the effects of constant hand offsets in six directions on user perception of the placement in regards to whether it felt *normal* or *not normal*. Participants repeatedly completed a target-touching task involving moving their virtual hand to a series of eight targets on the corners of a small cube in front of the user. Targets were arranged in order to represent a range of movements and locations a user may experience in a real VR application. This would provide us with thresholds that are more representative of user detection in real scenarios, rather than highly controlled scenarios.

We employed a within-subjects design with all participants experiencing all combinations of offset magnitudes and directions. Two independent variables were varied for applied offsets:

- Magnitude: 3 cm, 6 cm, 9 cm, 12 cm, 15 cm, 18 cm, 21 cm, 24 cm
- Direction: right, left, up, down, far, close

The maximum offset magnitude of 24 cm was chosen during pilots due to its high frequency of being classified as not normal. Directions are relative to the user's forward direction. Each pair of conditions was tested twice with an additional sixteen tests using no offset for a total of 112 data points (8*6*2 + 16) per user.

Our implementation for offset hands involved displacing the virtual hand by a fixed offset each frame. Offsets were applied using the formula:

$$\vec{P_v} = \vec{P_r} + \vec{O}$$

- $\vec{P_v}$ = the virtual hand position to be displayed
- $\vec{P_r}$ = the tracked position of the real hand in the virtual space
- $\vec{O}$ = the current offset vector applied

Our study design utilizes a 2AFC and psychophysical methods as our means of estimating detection thresholds. We chose to use "normal" and "not normal" (as used in previous detection studies for hand remapping [11]) as our response options for several reasons. Primarily, we are most interested in whether a hand placement feels natural to users as opposed to if they can detect placement towards one direction or the other. Because applications in a non-experimental context do not normally communicate hand offset directions directly to users, using natural placement as our criteria indicate how users *feel* about their hand placement. Additionally, we examined offsets in six directions along three axes at once rather than just two directions along one axis. Using "normal" and "not normal" instead of a direction-specific response (i.e., "left" and "right") provides more accurate estimations for the type of thresholds we seek to identify because in realistic scenarios users will not be directly told their hand is moved along a specific axis.

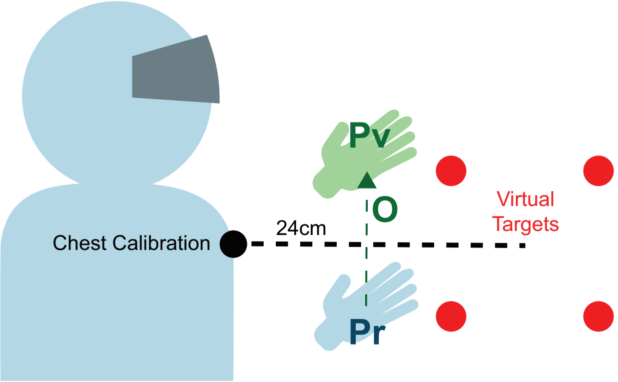

Figure 1: Generalized setup for the task. The center of the target group was placed 24 cm away from the chest of the participant. The real hand location $\vec{P_r}$ is offset by a constant vector $\vec{O}$ and is displayed to the user at location $\vec{P_v}$.

3.3 Participants

Participants were recruited from courses in our institution's computer science department. Extra course credit was used as compensation for participation. We recruited 19 participants (13 male, 6 female) with an average age of 23.5 years. While all participants completed the study with their right hand, three reported being predominantly left-handed. A majority of participants reported using VR technology only a few times before or never at all and were only somewhat familiar with VR.

3.4 Apparatus

All experiments were run in a designated lab space using an Oculus Rift HMD, the default Oculus tracking system, and the right and left Oculus Touch controllers. The controller used corresponded to the handedness of the participant. The application was developed using Unity 2019.2.16f1 and ran on a 64-bit Windows 10 Professional computer using a 4.6 Ghz 6-Core processor with a GeForce GTX 1080 8GB GDDR5X graphics card. In Unity one standard unit is equivalent to one meter, so offsets were converted from centimeters to meters for use in our application. All participants stood stationary in the same position on the ground marked with tape.

3.5 Procedure and Task

This procedure was approved by our institution's IRB. Informed consent was obtained from participants before beginning the experiment.

We chose a simple target-touching task for participants to complete while experiencing different offsets. Our task was designed to ensure all targets are normally in reach of the user to mimic the use case of these offsets for haptic retargeting and to require movement in three dimensions while using the hand.

In our task, a 24x24x24 cm cube was placed 24 cm away from the participant's chest via an initial calibration step to keep target placement similar between users. At each corner of the cube was a spherical target 7.5 cm in diameter. Figures 1 and 2 show the setup for each task. The sizes of the cube, targets, and distance from the user's chest were chosen during pilot studies to maximize comfort and reduce unnecessary stretching while touching each target. We chose these target locations to allow all targets to be consistently in the field of view of the participant to minimize search time as a factor in completing the task, as well as encourage hand movement along all three axes while completing the last.

All participants completed the experiment using their right hand, and their virtual hand was displayed as a model of the Oculus Touch

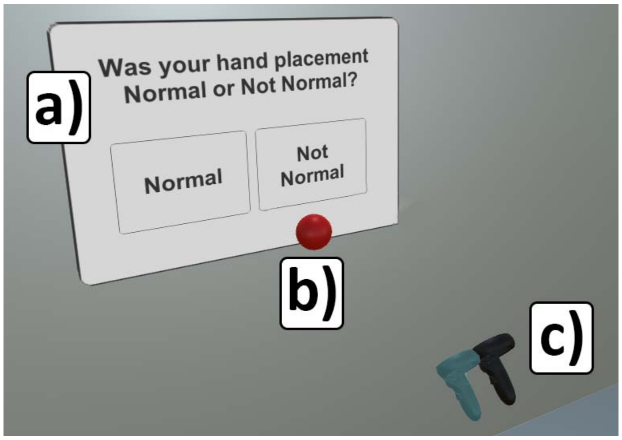

Figure 2: An image of the application environment. For the purpose of demonstrating the environment, some objects that would not normally be visible at the same time (i.e., the sign and target) are shown at the same time. **a)** The sign presented to users after completing each task. **b)** A target the user touched during the task. **c)** An offset hand (blue) and real hand (black). The virtual, offset hand is moved to the left of the real hand.

right controller they were holding. In each instance of the task, every target was tapped once and their order of appearance was randomized. Only one was target was shown at a time. After touching the final target, the hand was hidden from view until a response about its normality was given.

Participants were instructed to start each task with their hand at an idle position to their side, then tap each target with their hand as quickly as they could, then return their hand to their side before providing their answer. After returning to the side, a sign would appear in front of them asking if their hand placement was "normal" or "not normal". They were told how to use the joystick on the controller to toggle their answer to either "normal" or "not normal" (which was visible on the sign) and to use the back trigger button to confirm their answer. The hand became visible upon starting the next task.

After explaining the task to the participant, participants were asked to stand in a marked area on the floor and to hold their hand to their chest to calibrate the system based on their location and height to maintain consistency between participants. The participant then practiced the task and using the controller to select their answer until they were comfortable with the procedure. Participants were given both examples of normal placement using no offset and examples of not normal placement using large offset magnitudes.

After practice, participants began completing the tasks. A random list of each condition to be tested was generated and was used to determine the offset for each task. After each response, the current offset switched to the next while their hand was still hidden and out of sight. Breaks were offered frequently to reduce risk of sickness or arm fatigue due to repeated movements. The offset magnitude, offset direction, and related time measurements were logged.

When all tasks were completed, participants were given a demographics survey, the Simulator Sickness Questionnaire [20], and answered some final questions about their experience. Questions were qualitative in nature and aimed towards determining the difficulty of the task, perceived factors for determining hand normality, and other subjective thoughts about the task and experience.

4 RESULTS

First, we determined detection thresholds for offsets in each direction tested. We then examined how offset direction, magnitude, and limiting offsets based on thresholds affected task performance times.

Table 1: Detection thresholds and standard deviations for offsets. α values represent detection thresholds for each direction, while β values represent standard deviations. Confidence intervals express a 95% certainty that thresholds lay in the range presented.

Direction Thresholds and Standard Deviations

Axis	**Direction**	α**[CI]** (cm)	β**[CI]** (cm)
X	Right	9.40 [8.54, 10.24]	1.64 [1.41, 1.88]
	Left	10.27 [9.29, 11.30]	2.02 [1.74, 2.31]
Y	Up	12.83 [11.67, 14.12]	2.53 [2.15, 2.93]
	Down	13.37 [12.31, 14.48]	2.28 [1.95, 2.63]
Z	Far	13.25 [12.06, 14.38]	2.42 [2.08, 2.83]
	Close	7.83 [7.05, 8.59]	1.36 [1.15, 1.56]

4.1 Detection Threshold Estimates

We first began data analysis by estimating detection thresholds for offsets in each direction. User responses on the normality of their hand were logged for each offset used. These responses were aggregated into a total probability that users gave a *normal* response for each magnitude/direction pair, fit to a prediction function, and the fit curve used to determine a threshold value based on where the function equals a 0.5 probability. We utilized the *quickpsy* package [28] in R to generate thresholds and probability curves for each direction which handles grouping data points by direction, fits curves for each aggregated probability, and uses parametric bootstrapping to estimate confidence intervals (CIs) for each threshold generated. It fits data points to a function of the form

$$\Psi(x;\alpha,\beta,\gamma,\lambda) = \gamma + (1-\gamma-\lambda)F(x;\alpha,\beta)$$

where $F(x;\alpha,\beta)$ is a sigmoidal function with asymptotes at $y=0$ and $y=1$. γ and λ are parameters used to adjust the leftward and rightward asymptotes based on study design. In studies such as ours where probabilities at either extreme are near 0.0 or 1.0, it is acceptable to set γ and λ both to 0.0 [22], leaving the function as

$$\Psi(x;\alpha,\beta) = F(x;\alpha,\beta)$$

The logistic function is commonly used as $F(x;\alpha,\beta)$ to fit this type of data due to its asymptotic behavior at $y=0$ and $y=1$, corresponding to probabilities of 0.0 and 1.0 respectively. For purposes such as ours where γ and λ are both 0.0 and we are solely interested in generating thresholds, the choice of function has no significant impact on the threshold calculated [28]. The function takes the form

$$F(x;\alpha,\beta) = \frac{1}{1+exp(-\beta(x-\alpha))}$$

where α represents the *point of subjective equality* (e.g., the threshold value) and β is the associated standard deviation (e.g., the sensitivity of the curve to changes in offsets). Here, α exists at the point where the function is equal to a 50% probability. In our analysis, values less than α feel normal to most users while values greater than α will most likely feel not normal. CIs are calculated with parametric bootstrapping using a percentile method with 95% confidence α exists in the interval.

Fitted functions are shown in Figure 3 while precise α and β values are located in Table 1. Table 2 shows significant differences between detection thresholds for each offset direction and net differences between thresholds. These values were generated using the *thresholdcomparisons* function from the *quickpsy* R package, which performs a bootstrap comparison between all pairs of directions to determine if the difference between them falls outside a 95% CI.

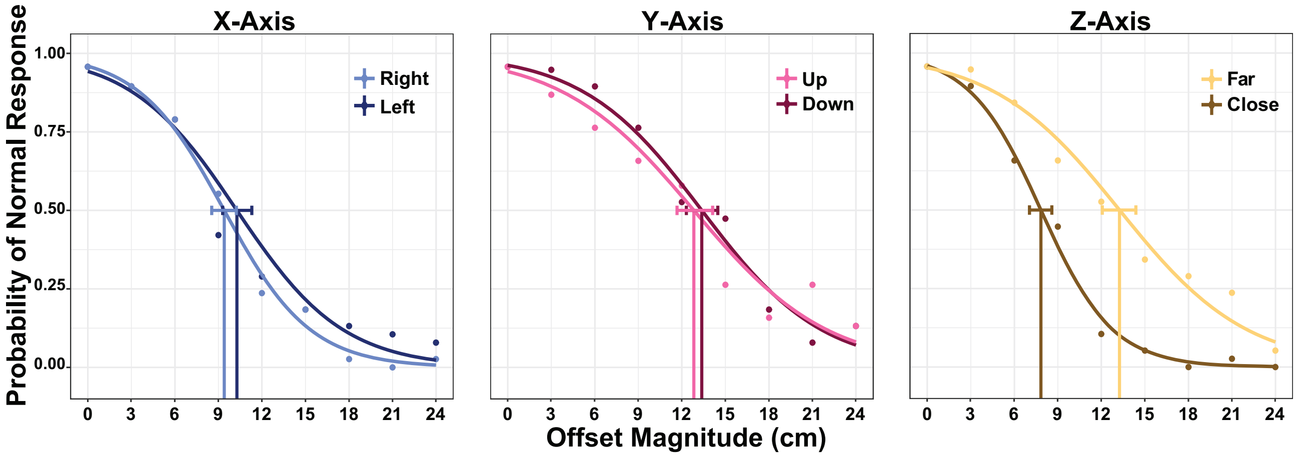

Figure 3: Fitted logistic functions for each direction, paired by axis of movement. Dropdown lines mark the threshold point. Error bars indicate 95% confidence intervals expressed in Table 1.

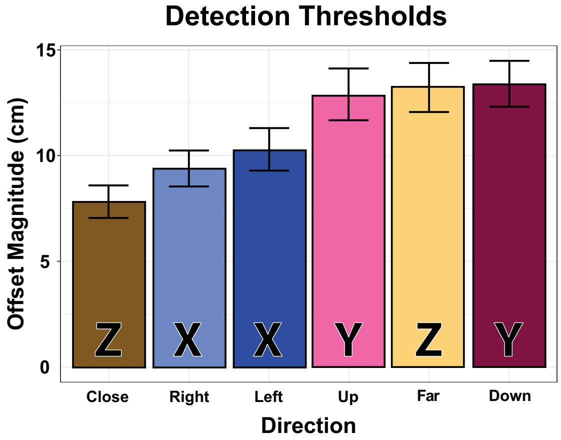

Figure 4: Detection thresholds for each direction, arranged from smallest to largest. The axis of displacement relative to the user located at the bottom of each bar. Error bars indicate 95% confidence intervals expressed in Table 1.

Table 2: Differences between direction thresholds (column minus row) in centimeters. Significance at $p < 0.05$ is indicated by **bold text** *.

Significance Between Thresholds

	Right	Left	Up	Down	Far	Close
Right	—	0.87	**3.42***	**3.96***	**3.84***	**-1.56***
Left	-0.87	—	**2.55***	**3.09***	**2.97***	**-2.44***
Up	**-3.42***	**-2.55***	—	0.54	0.42	**-4.99***
Down	**-3.96***	**-3.09***	-0.54	—	-0.12	**-5.53***
Far	**-3.84***	**-2.97***	-0.42	0.12	—	**-5.41***
Close	**1.56***	**2.44***	**4.99***	**5.53***	**5.41***	—

These findings provide evidence in favor of **H1** (detection thresholds will significantly differ between directions). Results shown in Table 2 and Figure 4 show that there are significant differences between thresholds for each direction. These thresholds range from a minimum of 7.83cm (3.08in) for the *close* direction to a maximum of 13.37cm (5.26in) for the *down* direction with a difference of 5.53cm (2.18in). When considering pairwise differences, three groupings emerge: *close* alone, a group of *right* and *left*, and a group of *up*, *far*, and *down*. Members of each group are not significant against other members. Axis-wise, only directions along the Z-axis were significantly different against each other which shows sensitivity to depth-related offsets.

4.2 Target Selection Performance

We also considered the effects of offsets on reaching performance for the target selection task. In our study design, accuracy was constrained since only one target was shown at a time, and the task required touching the target for completion. This leaves selection time as a performance measure for analysis. Selection times for the first target was discarded due to adjustments in user perception and expectations between trials.

4.2.1 Identifying Significant Factors for Target Selection

We first began this analysis by examining our data for general correlations between offset magnitude and selection times for each direction. Data was separated according to offset direction and Pearson's correlation was performed on each group to determine relationships between direction and magnitude on each target grouping. For every direction, correlations between offset magnitude and selection times were found to be positive. Figure 5 contains the average time for each magnitude and direction. While positive correlations were found, the overall effect observed is quite small.

To determine affects of offset direction and magnitude on selection times, we conducted a two-way repeated-measures ANCOVA with direction as a categorical independent variable and magnitude as a covariate. If the associated offset magnitude was below the threshold (but not zero) it was considered *within-threshold* or if it was above the threshold it was *exceeding-threshold*. If designers wish to use thresholds to create natural applications, it is important to know how limiting hand placements to exist within thresholds affects task ability.

Table 3 shows the significance of each factor on selection times for each offset group. Pairwise comparisons are not reported due to the large volume of pairs, however generally as the difference between

Table 3: Significance of offset direction and magnitude on target selection times as determined by our two-way repeated-measures ANCOVA for all offsets, offsets within the thresholds, and offsets exceeding the thresholds.

Significance of Factors on Target Selection Times

Offset Grouping	**Direction**		**Magnitude**		**Dir. × Mag.**	
	F(5, 90)	p	F(1, 18)	p	F(5, 90)	p
All Offsets	5.15	$<$ **0.001***	10.85	$<$ **0.001***	5.40	$<$ **0.001***
Within-Threshold	0.99	0.43	3.24	0.09	1.26	0.29
Exceeding-Threshold	5.08	$<$ **0.001***	28.25	$<$ **0.001***	3.21	$<$ **0.05** *

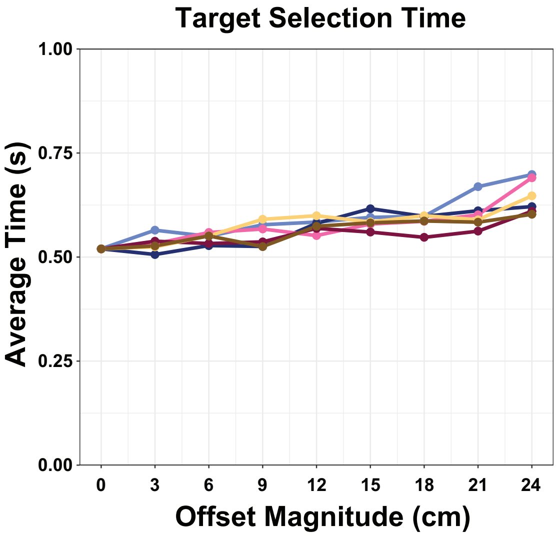

Figure 5: Average selection times for targets, based on offset and direction.

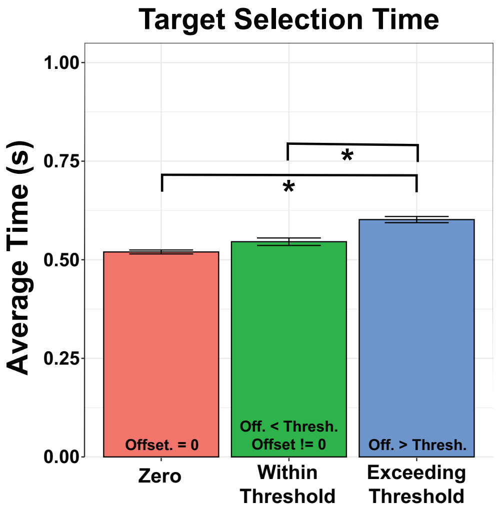

Figure 6: Average times for selection, grouped by zero, *within-threshold*, and *exceeding-threshold* offsets. Significance between offset groupings are marked by a line between bars (all significant at $p < 0.001$). Error bars indicate a 95% confidence interval.

offset magnitudes increase a significant difference is more likely to be observed. When looking at all offsets, both magnitude, direction, and the interaction effect between the two were significant for selection times. Interestingly, when considering only *within-threshold* offsets no factors significantly impacted selection time. When examining how *exceeding-threshold* offsets affect performance, both factors and their interaction were significant. This suggests that on the whole, performance while using *within-threshold* offsets are similar while performance with *exceeding-threshold* offsets can vary based on the offset.

4.2.2 Differences in Selection Based on Offset Limits

After determining that the significance of offset direction and magnitude varies if the offset is within or exceeds the threshold, we wanted to examine how times in each target grouping vary based on offset classifications. We utilized the same *within-threshold* and *exceeding-threshold* groupings, in addition to a third zero magnitude (*true normal*) grouping. We compared selection times between each offset grouping using a one-way repeated-measures ANOVA and found a significant main effect (F(2, 2125) = 28.76, $p < 0.001$). Additionally, a posthoc Tukey HSD test revealed the following:

- Exceeding vs. Within = 0.39, $\mathbf{p} < \mathbf{0.001}$*
- Zero vs. Within = -0.07, $p = 0.64$
- Zero vs. Exceeding = -0.47, $\mathbf{p} < \mathbf{0.001}$*

These results indicate no significant difference detected between *zero* and *within-threshold* offsets, but both *zero* and *within-threshold* were significantly different than *exceeding-threshold* offsets. Figure 6 shows average times for each target grouping. These findings suggest that offsets within the “normal-feeling” range performed similarly to unmodified hands, whereas larger offsets can influence performance as well as detection.

During analysis, we also examined *response time* (the time between touching the final target and providing a response), but did not find any significance under any condition or grouping. All average times were fairly consistent (between 1.2 and 1.4 seconds). We believe this to be a logical consequence of our study design. Since we required participants to touch an entire set of targets, they were likely able to determine normality before completing the trial so this time was based on how quickly users could use the controller to provide their answer.

5 DISCUSSION

We discuss how our findings should be utilized in the design of VR interaction techniques, identify limitations of our experiment, propose areas of further exploration, and provide answers to our two research questions:

- **Q1:** What are the maximum constant offsets that can be applied to a user’s virtual hand in each direction before it is perceptibly not normal, and how do they differ from one another?

- **Q2:** How do offset direction and magnitude affect target selection?

5.1 Detection of Offset Hands

Previous thresholds have been proposed for techniques that smoothly modify a hands position based on movement. For the first time, we provide estimated detection thresholds for constant hand offsets in six directions: *right* (9.4 cm), *left* (10.3 cm), *up* (12.8 cm), *down* (13.4 cm), *far* (13.2 cm), and *close* (7.8 cm). We found significant differences between thresholds (see Table 2), indicating that fixed offsets are not uniform for all directions a hand may be moved. When considering the axis of movement offset, significant differences were found only along the Z-axis (close/far offsets). Users were approximately 56.1% more sensitive to offsets that moved their hand closer to them than those that moved it away. Because no significant differences were found between offsets along the X and Y axes, we explored what factors our participants considered when determining their responses. Many participants commented during our post-survey that certain physiological factors, such as excessive arm-stretching or leaning, played a role in their ability to tell hand normality. These are exemplified by the following comments from participants:

- *"...I didn't have to* ***lean forward****, it felt normal."*
- *"...during most of the "not normal" choices, I found I had to* ***reach and stretch out more****."*
- *"If I had to* ***strain my arm*** *to reach a ball, the movement was not normal."*

This is likely why *close* offsets have the lowest threshold since a hand placed closer to the body requires more arm extension to reach a target in front of the user. Therefore, we encourage VR designers to pay specific attention to remapping techniques that require more physical movement from users compared to normal hands. If techniques introduce this additional movement, they are much more likely to be detectable. In contexts such as *exergames* [35] (games designed to encourage exercise and physical exertion) or medical rehabilitation [9] heightened or lessened movement could lead to better exercise-related outcomes. Making noticeable adjustments at a large magnitude may discourage users since it will become obvious they are making larger movements. Alternatively, smaller adjustments to make movements *easier* during cooldown periods of exercise could also be an application. However, further investigations into how much additional movement can be elicited from users via this technique would need to be investigated.

It is possible that these thresholds can be applied to other hand remapping techniques (i.e., [17, 31, 40]) as a limiting factor on the maximum hand displacement allowed. However, this would likely result in negative impacts on the range of areas where they could be used. For example, if these were used as limits for Han et al.'s [17] translational hand remapping for haptic use, the range of possible haptic prop locations would be limited. For smaller displacements between the virtual and real objects, minimal detection would be experienced. These trade-offs between perceived normality and range of use should be considered by designers, as increasing one is most likely to decrease the other.

We can also make general comparisons between our threshold estimates and those for other remapping techniques in regards to direction sensitivity. Most interesting are comparisons between our fixed positional offsets and Esmaeili et al.'s scaled movement [11] due to the consideration of directionality in both works. Axis-specific sensitivities were not consistent for movement based thresholds. For faster movement, users were least sensitive to scale movement along the Y-axis, followed by Z then X. For slower movement, Z was least sensitive followed by X, then Y. *Positionally*, we only found differences between offsets along the Z-axis (*close* being very sensitive and *far* being less sensitive) while Y-offsets were less sensitive than X-offsets. While the techniques differ, comparisons between axis-based sensitivities suggest that *movement* and *position* are in fact perceived differently. Further work that investigates the combined use of these techniques may be able to identify whether *movement* or *position* dominate over the other.

5.2 Effects of Offsets on Target Selection

Due to our study design, selection accuracy was constrained in our experimental task. We assessed the effects of offsets on different time measures. We identified significant differences between selection times for unmodified, *within-threshold*, and *exceeding-threshold* offset hands and determined that offset direction, magnitude, and their interaction effect are generally only significant factors for task performance if the offset is beyond the detection threshold.

During our analysis of the effects limiting offsets on selection times, no significant difference in times was detected between *within-threshold* and zero offsets. We believe that as long as a hand's offset is within the thresholds we propose, user performance will be comparable to that of an unmapped hand. This is specifically useful for situations where targets are located within or near the user's normal reach. For example, remapped hands used to facilitate haptics since users should still perform actions quickly while reaching for a haptic prop. In these cases hands are not remapped for extended reach but instead to realign hands towards a physical prop, so maintaining similar performance *and* natural feeling is especially advantageous. Our findings reinforce those of Han et al. [17], which found notable negative impacts of large offsets for haptic retargeting but little impact of small offsets in reach tasks.

We also examined user response time, but analysis failed to detect significance of experimental factors. This suggests that our study design and task provided enough time for participants to determine normality without much thought after finishing. This could indicate that humans can determine normality fairly quickly after being exposed to an altered hand placement if made aware of its presence. Future study designs that allow users to finish a task early if they determine normality may be able to provide more insight into just how quickly users are able to determine normality. This would have implications for scenarios where offsets or altered hand mappings may be changed quickly rather than gradually. It may be possible to apply larger magnitude offsets to hand for a short period of time that exceed our estimated thresholds.

5.3 Limitations

One limitation to our study is that all participants used their right hand to complete the tasks. Prior work in similar areas [15, 30, 40] found differences in detection for movements to the left and right. However because we did not detect significant differences between right and left offset detection thresholds for the right hand we do not suspect there to be any effect of handedness on these thresholds, though these should be considered in greater detail in future work.

Our thresholds are likely more lenient than thresholds determined by experiments that utilize more constrained movements. In prior research, a single target is placed in front of the user and the user extends their arm directly from their chest [15, 40]. For the purposes of our work (determining perception of "normal" hand movement), using less controlled movements is a more general representation of the types of movements users make in VR applications. Future work that examines more controlled movements or movements under different levels of distraction or complexity may determine thresholds that differ based on application context.

While we chose our target locations to represent a range of locations and movements that may be performed by a user, our choice of task and target locations may also influence our thresholds and task performance. Because all targets were in front of the users, thresholds may vary if target locations exist at the extremities of user reach, though we note that in most applications users will likely be interacting with objects in front of them. Scene complexity could also influence thresholds, with more complex scenes producing different thresholds.

We also acknowledge limitations of psychophysical methodologies. In our study, we chose to have users respond either *normal* or *not normal*, which may carry different meanings between users. User's may default to *not normal* if there is any doubt that the hand may not be normal. *Normal* and *not normal* responses may also produce different thresholds when compared to tests that presume every stimulus is not normal (e.g., [15, 38, 40]).

6 CONCLUSION

To our knowledge, our research is the first to present detection thresholds for *fixed offset* hand transformations in six offset directions. Previous investigations into detection of remapped hands have been limited to techniques that utilize a continuously changing offset. Depending on context, it can be advantageous to apply constant offsets rather than dynamically changing offsets. If designers utilize offset hands in applications, but seek to maximize realism or immersion, it is necessary to know maximum absolute distances hands can be moved before they are noticeable.

To determine these thresholds, we conducted a study using two-alternative forced-choice methodology to assess human perception of offset hand placement while completing a target-touching task. Our findings contribute to the understanding of human perception by providing limits on how far virtual hands can be displaced before they no longer feel normal to users. Thresholds were found to significantly vary based on direction, indicating that there is not one distance detection distance and that each direction should be considered separately. The offsets were also significantly related to performance using the hand. Specifically, offset hands kept within these thresholds performed comparably to hands without an offset while hands that exceeded the thresholds resulted in lessened performance.

These thresholds can be used in conjunction with hand remapping techniques in order to maximize their perceived normality. Application context is also an important consideration, as applications that use remapped hands to heighten user ability to reach and manipulate their scene may desire to sacrifice naturalism in favor of stronger interactions.

REFERENCES

[1] 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*, CHI '16, p. 1968–1979. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2858036.2858226

[2] G. Bruder, P. Lubos, and F. Steinicke. Cognitive resource demands of redirected walking. *IEEE Transactions on Visualization and Computer Graphics*, 21(4):539–544, 2015.

[3] E. Burns and F. P. Brooks. Perceptual sensitivity to visual/kinesthetic discrepancy in hand speed, and why we might care. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology* VRST '06, p. 3–8. Association for Computing Machinery, New York, NY, USA, 2006. doi: 10.1145/1180495.1180499

[4] 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 *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pp. 3–10, March 2005. doi: 10.1109/VR.2005.1492747

[5] E. Burns, S. Razzaque, M. C. Whitton, and F. P. Brooks. Macbeth: Management of avatar conflict by employment of a technique hybrid. *IJVR*, 6:11–20, 2007.

[6] L.-P. Cheng, E. Ofek, C. Holz, H. Benko, and A. D. Wilson. Sparse haptic proxy: Touch feedback in virtual environments using a general passive prop. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, p. 3718–3728. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3025453.3025753

[7] C. Cruz-Neira, D. J. Sandin, and T. A. DeFanti. Surround-screen projection-based virtual reality: The design and implementation of the cave. In *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '93, p. 135–142. Association for Computing Machinery, New York, NY, USA, 1993. doi: 10.1145/166117.166134

[8] L. Dominjon, A. Lecuyer, J. . Burkhardt, P. Richard, and S. Richir. Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pp. 19–25, March 2005. doi: 10.1109/VR.2005.1492749

[9] P. S. Dukes, A. Hayes, L. F. Hodges, and M. Woodbury. Punching ducks for post-stroke neurorehabilitation: System design and initial exploratory feasibility study. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 47–54, 2013.

[10] 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 Trans. Appl. Percept.*, 13(4), July 2016. doi: 10.1145/2947617

[11] S. Esmaeili, B. Benda, and E. D. Ragan. Detection of scaled hand interactions in virtual reality: The effects of motion direction and task complexity. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, March 2020.

[12] T. Feuchtner and J. Müller. Extending the body for interaction with reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, p. 5145–5157. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3025453.3025689

[13] S. Frees and G. D. Kessler. Precise and rapid interaction through scaled manipulation in immersive virtual environments. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pp. 99–106, March 2005. doi: 10.1109/VR.2005.1492759

[14] G. A. Gescheider. *Psychophysics*. Psychology Press, 1997. doi: 10.4324/9780203774458

[15] E. J. Gonzalez and S. Follmer. Investigating the detection of bimanual haptic retargeting in virtual reality. In *25th ACM Symposium on Virtual Reality Software and Technology*, VRST '19. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3359996.3364248

[16] T. Grechkin, J. Thomas, M. Azmandian, M. Bolas, and E. Suma. Revisiting detection thresholds for redirected walking: Combining translation and curvature gains. In *Proceedings of the ACM Symposium on Applied Perception*, SAP '16, p. 113–120. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2931002.2931018

[17] D. Han, M. S. Mohamed Yousuf Sait, and E. Ragan. Evaluating remapped physical reach for hand interactions with passive haptics in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, PP:1–1, 01 2018. doi: 10.1109/TVCG.2018.2794659

[18] D. Hayashi, K. Fujita, K. Takashima, R. W. Lindeman, and Y. Kitamura. Redirected jumping: Imperceptibly manipulating jump motions in virtual reality. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 386–394, 2019.

[19] V. Interrante, B. Ries, and L. Anderson. Seven league boots: A new metaphor for augmented locomotion through moderately large scale immersive virtual environments. In *2007 IEEE Symposium on 3D User Interfaces*, March 2007. doi: 10.1109/3DUI.2007.340791

[20] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, 3(3):203–220, 1993. doi: 10.1207/s15327108ijap0303_3

[21] F. A. A. Kingdom and N. Prins. *Psychophysics: A Practical Introduction*. Academic, 2010.

[22] K. Knoblauch and L. Maloney. *Modeling Psychophysical Data in R*. 01 2012. doi: 10.1007/978-1-4614-4475-6

[23] L. Kohli. Exploiting perceptual illusions to enhance passive haptics. In *IEEE VR Workshop on Perceptual Illusions in Virtual Environments (PIVE)*, pp. 22–24, 2009.

[24] L. Kohli, M. C. Whitton, and F. P. Brooks. Redirected touching: The effect of warping space on task performance. In *2012 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 105–112, March 2012. doi: 10.1109/3DUI.2012.6184193

[25] L. Kohli, M. C. Whitton, and F. P. Brooks. Redirected touching: Training and adaptation in warped virtual spaces. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 79–86, March 2013. doi: 10.1109/3DUI.2013.6550201

[26] J. Li, I. Cho, and Z. Wartell. Evaluation of 3d virtual cursor offset techniques for navigation tasks in a multi-display virtual environment. In *2015 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 59–66, 2015.

[27] J. Li, I. Cho, and Z. Wartell. Evaluation of cursor offset on 3d selection in vr. In *Proceedings of the Symposium on Spatial User Interaction*, SUI '18, p. 120–129. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3267782.3267797

[28] D. Linares and J. López-Moliner. quickpsy: An R Package to Fit Psychometric Functions for Multiple Groups. *The R Journal*, 8(1):122–131, 2016. doi: 10.32614/RJ-2016-008

[29] B. Matthews, B. Thomas, S. Itzstein, and R. Smith. Remapped physical-virtual interfaces with bimanual haptic retargeting. 04 2019. doi: 10.1109/VR.2019.8797974

[30] N. Ogawa, T. Narumi, and M. Hirose. Effect of avatar appearance on detection thresholds for remapped hand movements. *IEEE Transactions on Visualization and Computer Graphics*, pp. 1–1, 2020.

[31] I. Poupyrev, M. Billinghurst, S. Weghorst, and T. Ichikawa. The go-go interaction technique: Non-linear mapping for direct manipulation in vr. *Proc. of UIST'96*, 09 1998.

[32] S. Razzaque, Z. Kohn, and M. C. Whitton. *Redirected walking*. Citeseer, 2005.

[33] S. Razzaque, D. Swapp, M. Slater, M. C. Whitton, and A. Steed. Redirected walking in place. In *Proceedings of the Workshop on Virtual Environments 2002*, EGVE '02, p. 123–130. Eurographics Association, Goslar, DEU, 2002.

[34] S. P. Sargunam, K. R. Moghadam, M. Suhail, and E. D. Ragan. Guided head rotation and amplified head rotation: Evaluating semi-natural travel and viewing techniques in virtual reality. In *2017 IEEE Virtual Reality (VR)*, pp. 19–28, March 2017. doi: 10.1109/VR.2017.7892227

[35] J. Sinclair, P. Hingston, and M. Masek. Considerations for the design of exergames. In *Proceedings of the 5th International Conference on Computer Graphics and Interactive Techniques in Australia and Southeast Asia*, GRAPHITE '07, p. 289–295. Association for Computing Machinery, New York, NY, USA, 2007. doi: 10.1145/1321261.1321313

[36] T. Stebbins and E. D. Ragan. Redirecting view rotation in immersive movies with washout filters. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 377–385, March 2019. doi: 10.1109/VR.2019.8797994

[37] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Analyses of human sensitivity to redirected walking. In *Proceedings of the 2008 ACM Symposium on Virtual Reality Software and Technology*, VRST '08, p. 149–156. Association for Computing Machinery, New York, NY, USA, 2008. doi: 10.1145/1450579.1450611

[38] 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*, 16(1):17–27, Jan 2010. doi: 10.1109/TVCG.2009.62

[39] J. Wentzel, G. d'Eon, and D. Vogel. Improving virtual reality ergonomics through reach-bounded non-linear input amplification. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3313831.3376687

[40] A. Zenner and A. Krüger. Estimating detection thresholds for desktop-scale hand redirection in virtual reality. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 47–55, March 2019. doi: 10.1109/VR.2019.8798143