

Performance Evaluation of Warped Virtual Surfaces in Virtual Reality

by

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Abstract

This thesis proposes a novel surface warping (scaling) technique similar to applying Control-Display (CD) gain to the traditional mouse cursor on a screen with a 1:1 input device in Virtual Reality (VR). We call the technique Warped Virtual Surfaces (WVS). WVS solution is a promising way of providing large tactile surfaces in VR while using small physical surfaces with little impact on user performance. We utilized a stylus with VR head-mounted displays (HMDs), enabling users to interact with arbitrarily large virtual panels in VR while their real physical movement is within a fixed-sized real panel area. WVS on a tablet or a physical panel would entail users interacting with larger virtual panels while getting the benefits of haptic feedback from a smaller real physical panel or tablet. We evaluated the WVS method in two separate experiments. Experiment results from Fitts' law reciprocal tapping task comparing different scale factors (SFs) indicated there was a significant difference in movement time for large scale factors in both experiments. We first evaluated user performance on a digital drawing tablet and stylus with 2D tracking with WVS under different SFs. In the case of throughput and error rate, the analysis did not find a significant difference between scale factors in our first study. Non-inferiority statistical testing revealed that performance in terms of throughput and error rate for large scale factors was no worse than a 1-to-1 mapping. This indicates that warping had minimal impact on performance. For our second study, we investigated how WVS affected user performance with 3D stylus tracking and without a tablet or physical panel (i.e. in-air selection). We found similar results for error rate as our first study, i.e. performance in terms of error rate for different scale factors, was no worse than a 1-to-1 mapping. However, unlike our first study, our analysis found a significant difference in throughput.

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Dissemination of Thesis

The first study in this thesis was published as a full paper in the Graphics Interface (GI) 2020 conference:

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Link to online paper presentation:

<https://www.youtube.com/watch?v=AIYdqG5SphU>

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Chapter 1: Introduction

Virtual reality (VR) takes advantage of display and tracking technologies to immerse the user in computer-generated 3D environments that do not necessarily follow the physical rules of reality. In recent years, there has been a surge in demand for VR in entertainment, education, and design applications. The new generation of VR hardware, including head-mounted displays (HMDs) and VR capable graphics cards, are becoming more affordable. HMD-based VR is becoming self-contained, wireless, lighter, and has higher visual fidelity. Tracking systems are becoming increasingly more reliable and are capable of tracking hands, fingers and a higher number of objects with ever-increasing accuracy. Development tools like Unity3D¹ and Unreal Engine² have also become free for personal use and more accessible. Indeed, thanks to games such as Beat Saber³, Half-Life Alyx⁴ or the Lab⁵, VR is starting to appeal to a broader audience. All these factors have created the perfect storm, paving the way for a new wave of innovations and creativity in immersive VR technologies.

Universal interaction tasks for immersive VR environments include navigation, selection, manipulation, system control and symbolic input. Selection is perhaps the most important of these since it is embedded in the other tasks. Users must select an object before manipulating it; for navigation, users must first select a destination (e.g. choosing a

¹ <https://unity.com/>

² <https://www.unrealengine.com/>

³ <https://beatsaber.com/>

⁴ <https://www.half-life.com/en/alyx/>

⁵ https://store.steampowered.com/app/450390/The_Lab/

teleportation location) and they must select menu icons or buttons for system control and symbolic input.

VR scholars have come up with a variety of selection and manipulation techniques for VR over the years in tandem with advances in tracking and display technologies. Despite these advances, 3D interaction is still awkward [15], and there remain challenging research problems to be solved. There are many problems facing scholars and engineers in coming up with a universal best 3D interaction technique, such as interacting with 3D objects over a distance or selecting targets in densely packed virtual environments (VEs).

General-purpose haptics, i.e. the ability to present a proper sense of touch for virtual objects, is among these big problems. Past research has demonstrated that haptic feedback significantly increases the quality of a VR experience for users [31, 35, 39, 57]. However, designing interaction techniques and input methods that support realistic haptic feedback in VR is problematic even with the current state of technological innovations.

From a high-level, there are two basic approaches to designing for haptics support for interaction techniques in VR. One is to use actuated input devices like the Phantom⁶ that provide force feedback. The other approach is using props that correspond to virtual objects in the scene. See Figure 1 for examples of such approaches. Neither approach provides a perfect solution. Current haptic devices require sophisticated hardware that supports only a few contact points. Devices such as the Phantom support only one single contact point in a limited operational range and are expensive. Utilizing a stylus, users can interact with an object and receive the appropriate force feedback with the Phantom.

⁶ <https://www.3dsystems.com/haptics-devices/3d-systems-phantom-premium>

However, if users push the stylus with forces more than what the motors inside the Phantom can handle, it will result in *squishy* like force back, which breaks the experience.

Props, on the other hand, necessitate a large number and variety of objects to support a broad range of objects in VR and limit the number of objects one can have in a VE to the physically available ones. There is also the cost of tracking all the objects and the problems that arise due to objects occluding one another. Current VR platforms come with 3D tracked controllers with different input buttons and haptic support (vibrations). These controllers work well in the context of most VR games and they are used in most of the current VR applications (see Figure 1). In short, it is difficult to generalize and come up with a standard for 3DUIs, especially if we want to support haptics.

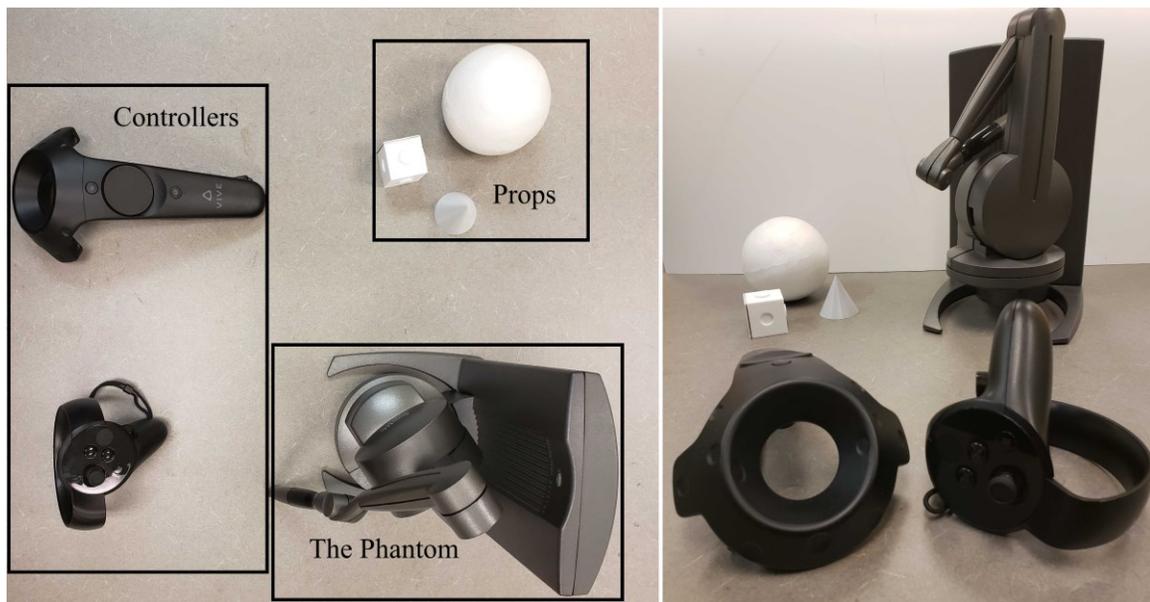


Figure 1: Different kinds of devices used to support haptic feedback in VR, including controllers that come with the Vive⁷ and the Oculus⁸ VR platforms, 3D printed props and a Phantom.

⁷ <https://www.vive.com/>

⁸ <https://www.oculus.com/>

Past studies have demonstrated the effectiveness of planar surfaces as a semi-general-purpose prop in VR. In particular, the use of tablets to provide tactile surfaces in VR has been extensively studied [16, 23, 50, 61, 70, 71, 76]. The Personal Interaction Panel (PIP) [71], Lindeman et al.'s HARP system [50], the Virtual Notepad by Poupyrev et al. [61], and Worlds In Miniature (WIM) [70] all used tracked panels for VR interaction. Other studies used a tablet and stylus for text input in VR [16]. Stylus or touch (i.e. fingers) are the two input modalities commonly used with planar surfaces like tablets. Although stylus and pen are proven effective [60], there is an absence of tablet or stylus devices designed specifically for VR with very few exceptions like Logitech VR Ink⁹.

Several researchers have investigated the use of redirection and retargeting techniques for VR interaction. This relatively new class of perceptual illusion-based interaction techniques include techniques like redirected walking (RDW) [64], haptic retargeting [6] and redirected touch [43–45]. Except for Yang et al.'s VRGrabber technique, which used retargeting with grabbing tools [80], all other techniques apply warping or redirection to the entire body (e.g., with RDW), or a body part such as the hand or fingers. These types of interaction techniques enable small physical motions to map onto large virtual motions. In other words, they do not do a 1-to-1 mapping between the physical motion and movement of users and the virtual motion and movement they see in VR. This allows users to move through larger VEs than that physically available, or to repurpose tangible objects as several virtual objects, without realizing they are using the same physical object.

⁹ <https://www.logitech.com/en-roeu/promo/vr-ink.html>

None of the proposed interaction techniques so far have been applied with a planar surface, despite the well-known benefits of using these in VR. Warping on planar surfaces would allow users to take advantage of a larger workspace in VR with a small tactile surface for haptic feedback. Although there are studies on bimanual retargeting [56] or unimanual redirected touching that used planar surfaces in their experiments [44, 45], none studied the planar surface as a means of input method. Large displays are known to offer performance benefits on spatial tasks, spatial knowledge, and navigation [7, 72, 73]. Hence, we propose to use space warping to extend the interaction panel surface in VR.

1.1 Contributions

We propose a technique we call Warped Virtual Surfaces (WVS). WVS combines the ideas behind RDW [64] in expanding the limited tracking area for walking, and the body warping approach in haptic retargeting [6] to create the perceptual illusion of a bigger VR panel. With WVS, users can interact with an arbitrarily large tactile virtual surface in HMD-based VR while using a fixed-sized physical panel. We conducted two studies to evaluate WVS in different scenarios, one with a tracked tablet, and the other with in-air stylus motions.

For our first experiment, we employed a fixed-size 3D tracked physical tablet that used a stylus for input but did not support 3D tracking for the stylus. Stylus tracking employed the tablet’s digitizer in 2D, i.e., the 2D location the users were pointing with the stylus tip on the physical tablet’s surface was shown as a cursor on the virtual panel in VR. The physical tablet provided haptic feedback to the user.

In our second experiment, we assessed user selection performance without physical tactile panels present (i.e., in-air selection) and used a 3D tracked stylus. Our objective was to determine how WVS would affect user selection performance without a physical panel

present and with 3D stylus tracking. We compared two different interaction modes for the 3D tracked stylus: *Snap* vs. *No-Snap*. Snapping would prevent the stylus from passing through the virtual panel in VR and was the closest condition that could mimic interactions on a physical tactile panel. No-Snap was the classic VR interaction technique in our study, i.e. pure in-air interactions, requiring some depth accuracy from the user.

In both experiments, the WVS technique applied a scale factor (SF) to move the virtual stylus/cursor beyond the real tactile panel or tablet's rectangular area (*height* and *width*). Warping entailed the stylus to behave like an indirect input device, similar to a mouse cursor and akin to changing the control-display (CD) gain (CD gain is a unit free coefficient that maps the movement of the pointing device to the movement of the display pointer) [5, 54]. With WVS and HMD-based VR, users cannot directly see their hands or physical stylus. Hence, they tend not to notice the decoupling between the physical stylus/cursor and the virtual stylus/cursor in VR. In a typical (i.e., non-VR) setup, this would be distracting and confusing to the user.

Different scale factors cause the cursor or the virtual stylus to move further with less physical movement, much like how CD gain works for a mouse cursor. However, the user perceives the virtual contact on the surface in VR and thus receives appropriate tactile cues from physically touching the tactile panel or tablet with the stylus. WVS creates the illusion of an arbitrarily large tactile surface in VR while keeping the users' motor space consistent during interaction on the tactile panel or tablet. We demonstrate our technique by implementing it on a digital drawing tablet with a stylus, equipped with an HTC Vive tracker. We also developed a version without the presence of a physical tactile panel or tablet. We employed in-air gestures and snapping, i.e. preventing the virtual stylus from

passing through the virtual panel in VR. We envision WVS could be useful with small, lightweight arm or wrist-mounted touchscreens to facilitate tactile interaction with 3D menus or similar applications to PIP and WIM [70, 71]. Since WVS uses cheap and available hardware, we believe it will also be beneficial for artists and designers.

To evaluate user performance, we employed a Fitts' law reciprocal tapping task [30, 74]. To our knowledge, our experiment is the first to investigate the effects of surface warping using a stylus on user performance in selection tasks, and to apply CD gain with a tablet and stylus input modality in VR.

1.2 Thesis Outline

Chapter 2 will touch on past research on how visual illusions work and smart ways scholars took advantage of visual illusions to create interaction techniques in VR. We also briefly explain Fitts' law [30] and non-inferiority statistical analysis [67] used in our statistical analysis. Chapter 3 is devoted to explaining the WVS interaction technique. Chapter 4 is on the feasibility of the WVS approach with fixed physical panel size and its effect on selection performance. We showed that performance in terms of throughput and error rate remained constant regardless of SF. Chapter 5 is on the effects of WVS on user performance without a tactile physical panel and in-air interactions with a 3D tracked stylus. Results indicated a significant difference between SFs for TP but not for error rate. Ultimately, in Chapter 6, we will provide discussions on our findings, the limitations, and the future of WVS.

Chapter 2: Related Work

In this chapter, we first provide some background on 3D interaction techniques in VR and past studies that inspired this work on visual illusions. We also explain Fitts' law methodology (section 2.4) [30] and non-inferiority testing (section 2.6) for statistical analysis [67].

2.1 3D Interaction Techniques in VR

Immersed users in a VR setting can interact with the VE with six independent degrees of freedom (DOF), translation along and rotation about each of the x , y , and z axes. Interaction techniques are required to accomplish all the canonical interaction tasks: selection, manipulation, navigation (i.e. travel and wayfinding), system control and symbolic input.

Navigation is determining course or a trajectory to an intended location in the VE and it comprises two sub-tasks: travel (i.e. the actual motion) and wayfinding (i.e. the cognitive process of defining a path to the intended location). System control focuses on issuing commands to change the state of the VR system. Symbolic input is related to tasks like text entry in VR. Selection is defined as specifying an object for subsequent interaction, similar to clicking an icon on a desktop computer system. Manipulation is modifying the objects' position, size or rotation [15]. This thesis focuses on selection tasks and provides a novel interaction technique that could be used for stylus selection and manipulation techniques.

Many VR selection techniques are hand-based, requiring the use of the user's hands directly or ray-based (in-directly), requiring the use of remote pointing (e.g., with a controller). Interaction techniques in VR do not need to always comply with the rules of physical reality. For example, some hand-based techniques enable users to either interact

with remote objects directly, such as the Go-Go interaction technique [62] or indirectly, as seen in worlds-in-miniature (WIM) [70], where users interact with a smaller version of objects in the VE on a tablet-like device. Factors that affect user performance in a selection task are the target size and how far the target object is (as described by Fitts' law [30], which is further explained in section 2.4), the density of the objects in the VE [78].

HCI scholars have also attempted to come up with non-hand-based approaches for interaction in VR. Head and eye-tracking are among such methods. They have been employed and studied both in isolation and combination for selection tasks. Qian et al. [63] evaluated selection performance using eye and head tracking in a Fitts' law experiment. Their results indicated that eye-only tracking performed the worst while head-only tracking performed better.

2.2 Visual Illusions

Studies on the human brain revealed the dominance of vision over other senses when there are sensory conflicts [11, 21, 26, 32, 33, 66, 69]. For instance, Gibson showed that a flat surface is perceived as curved while wearing distortion glasses and moving hands in a straight line [32]. Similarly, other studies showed that participants believed the distorted images of objects over the shape they felt while wearing a distortion lens and holding the object through a cloth [66].

These illusions rely on the inaccuracy inherent to our proprioception and vestibular senses [11]. Burns et al. provided evidence of visual dominance over proprioception in a series of studies and found that people tend to believe their hand is where they see it [18–20]. Klatzky et al. showed that vestibular cues are also dominated by vision [42]. There is also evidence that visual dominance influences how we perceive our bodies, such as

owning a smaller body (i.e. different height and size) [8], having a bigger belly [59], or a longer arm length [41]. Visual dominance can also induce actions, such as speaking or walking [9, 46]. Other techniques rely on certain VE conditions to elicit fake or scaled body parts without significantly affecting body ownership [4, 13, 28]. (i.e. the feeling one attributes to external objects as a body part [14]).

These ideas have been applied in various HCI contexts. For example, Zenner et al. used an internal weight shifting mechanism in a passive haptic proxy to enhance virtual object length and thickness perception with Shifty [82]. Similarly, Krekhov et al. used weight perception illusions in a self-transforming controller to enhance VR player experience [48]. McClelland et al. introduced the Haptobend, which used a bendable device to support different objects with simple geometry such as tubes and flat surfaces with a single physical prop [57]. Other VR and HCI researchers took advantage of visual dominance to enhance selection in VR [4, 58, 62, 77], yielding several novel interaction techniques for HMD-based VR.

It is worth noting that vision is not always dominant over other senses, and in the case of conflicts, sensory signals are weighted based on reliability in the brain [34, 36]. There are thresholds on the dominance of vision. Scholars employed either just noticeable difference (JND) threshold methodology or two-alternative forced-choice (2AFC) to quantify mismatch thresholds [18, 38, 49, 55, 65, 81]. Force direction and the curvature of physical props are known to influence mismatch thresholds on the dominance of vision over proprioception [10, 65].

2.3 Perceptual Illusions in Virtual Reality

Likely the most well-known example is redirected walking (RDW), first proposed by Razaque et al. [64]. RDW enables users to walk an infinite straight virtual space in HMD VR. In reality, RDW users are walking in circles in a limited tracking space but perceive themselves as walking on straight lines.

Kohli et al. were among the first to propose redirected touching in a VR setting [43]. In a series of experiments, Kohli et al. looked into the effects of warping virtual spaces on user performance and adaptation and training under warped spaces [44, 45]. They reported that while training under real conditions seemed more productive, after adapting to discrepancies between vision and proprioception, participants performed much better [45]. Indeed, they reported that participants had to readapt to the real world after adapting to the warping virtual space [45].

Azmandian et al. [6], took the idea of redirected touching further and introduced haptic retargeting, which added dynamic mapping of the whole hand rather than just the fingers. Haptic retargeting partially solves a significant limitation of using physical props for tactile feedback by mapping one physical object to multiple virtual ones. The technique operates by redirecting the user's hand towards the physical prop when they are reaching for different virtual items at various locations [6].

Haptic retargeting and similar techniques work through perceptual illusions and the dominance of vision over other senses [11, 32, 42, 55, 66, 69]. The technique leverages visual dominance to repurpose a single passive haptic prop for various virtual objects. This approach produced a higher sense of presence among participants, in line with past findings on the benefits of haptics in VR [39]. The shape of the physical props is a major limitation

of the haptic retargeting technique, which one can partially solve with approaches similar to the Haptobend [57].

Another limitation of haptic retargeting is the target position, which must be known before selection. To overcome the targeting limitations in haptic retargeting, Murillo et al. proposed a multi-object retargeting technique by partitioning both virtual and physical spaces using tetrahedrons to allow open-ended hand movements while retargeting [58]. More recently, Matthews et al. demonstrated haptic retargeting for bimanual interactions [56]. They suggested that the technique could also be applied to wearables interfaces, i.e., on the user's wrist or arm [56].

Several other studies employed similar techniques to haptic retargeting to support haptics and better ergonomics for interactions in VR. For example, Cheng et al. explored the applications and the limits of hand redirection using geometric primitives with touch feedback in a VE while predicting the desired targets using hand movements and gaze direction [24]. Feuchtner et al. proposed the Ownershift interaction technique to ease over the head interaction in VR while wearing an HMD [29]. Ownershift does not require a mental recalibration phase since the initial 1:1 mapping allowed initial ballistic movements toward the targets [29]. Abtahi et al. utilized visuo-haptic illusions in tandem with shape displays [1]. They were able to increase the perceived resolution of the shape displays for a VR user by applying scales less than 1.8x, redirecting sloped lines with angles less than 40 degrees onto a horizontal line.

Table 1 summarizes key studies on perceptual illusions in VR. Most techniques are developed for unimanual hand interactions, with a few exceptions that used redirection techniques on controllers or props. To summarize, despite the well-known advantages of

large displays and planar surfaces in VR, very few studies have used warping techniques with planar input devices. Our proposed technique and present thesis aim to fill this gap.

1st Author/Year	Description	Evaluation Method	Redirection on	Main Findings	Notes
Kohli/2010 [43, 44, 45]	Redirected touch under warped spaces.	Fitts' law	Fingers	Discrepant conditions are no worse than 1-to-1 mapping.	Also evaluated performance & adaptation under warped spaces.
Azmandian/2016 [6]	Repurposing a passive haptic prop using body, world & hybrid space warping.	Block stacking	Hands	Hybrid warping scored the highest presence score.	Recommended encouraging slow hand movements & taking advantage of visual dominance.
Carvalho/2016 [21]	Haptic interaction system for VR & evaluating user awareness regarding the space warping.	Touch & moving objects	Hands	Average accuracy error of 7mm, users adapt to distortion & are less sensitive to negative distortions.	7 participants did not detect distortions, even though they were told about it in the second phase of experiments.
Murillo/2017 [58]	Multi-object retargeting optimized for upper limb interactions in VR.	Target selection.	Hands	Improved ergonomics with no loss of performance or the sense of control.	Used tetrahedrons to partition the physical and virtual world for multi-object retargeting.
Cheng/2017 [24]	Sparse haptic proxy using gaze and hand movement for target prediction.	Target acquisition	Hands	Retargeting of up to 15° similar to no retargeting, 45° received lower but above natural ratings.	Predicted desired targets 2 seconds before participants touched with 97.5% accuracy.
Han/2018 [33]	Static translation offsets vs. dynamic interpolations for redirected reach.	Reaching for objects.	Hands	The translational technique performed better, with more robustness in larger mismatches.	Horizontal offsets up to 76cm applied when reaching for a virtual target were tolerable.
Yang/2018 [80]	Virtual grabbing tool with ungrounded haptic retargeting.	Using the controller for precise object grabbing	Controller	Travelling distance difference between the visual and the physical chopstick needs to be in the range (-1.48,1.95) cm.	Control/Display ratio needs to be between 0.71 and 1.77 & better performance with ungrounded haptic retargeting.
Feuchtner/2018 [29]	Slow shift of users' virtual hand to reduce the strain of in-air interaction.	Pursuit tracking	Hands	Vertical shift hand by 65cm reduced fatigue and maintained body ownership.	Vertical shift decreases performance by 4% & gradual shifts are preferable.
Matthews/2019 [56]	Bimanual haptic retargeting with interface, body & combined warps.	Pressing virtual buttons	Hands/ Bimanual	Faster response time for combined warp. increased error in body warp.	Same time and error between bimanual and unimanual retargeting.

Table 1: Summary of Studies and their findings on redirection and space warping techniques.

2.4 Fitts' Law

Our study employs a Fitts' law task, briefly described here. Fitts' law predicts selection time as a function of target size and distance [30]. The model is given as:

$$MT = a + b \cdot ID \text{ where } ID = \log_2 \left(\frac{A}{w} + 1 \right) \quad \text{Equation 1}$$

where MT is movement time, and a and b are empirically derived via linear regression. The ID is the *index of difficulty*, the overall selection difficulty, based on A , the amplitude (i.e., distance) between targets, and W , the target width. As seen in Equation 1, increasing A or decreasing W increases ID , yielding a more laborious task. Figure 2 illustrates the selection task. Users must select the highlighted target repeatedly; the target moves as indicated by the arrows showing the target location for the next selection trial.

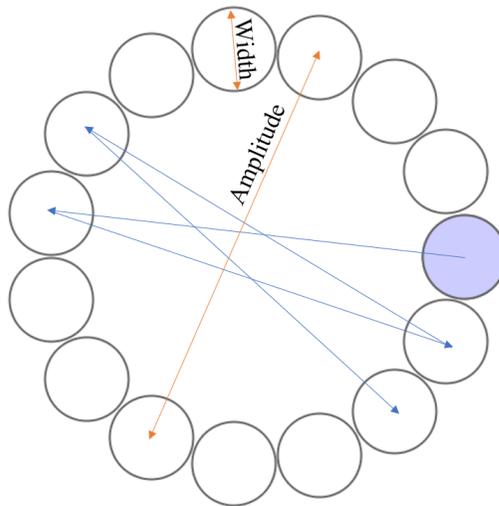


Figure 2: Fitts' law task, arrows indicate where the target would move after each selection.

Through the so-called accuracy adjustment, throughput combines speed and accuracy and is unaffected by the speed-accuracy trade-off commonly seen in such tasks [52]. It is thus widely used and recommended by the *ISO 9241-9* standard as a primary metric for pointing device comparison. In our experiments, we employ this methodology

and throughput for consistency with other studies [40, 74, 75]. Throughput measured in bits per second (bps) is given as:

$$TP = \frac{ID_e}{MT} \text{ where } ID_e = \log_2 \left(\frac{A_e}{W_e} + 1 \right) \quad \text{Equation 2}$$

ID_e is the effective index of difficulty and gives difficulty of the task users actually performed, rather than that they were presented with. Effective amplitude, A_e , is the mean movement distance between targets for a particular condition. Effective width, W_e is:

$$W_e = 4.133 \cdot SD_x \quad \text{Equation 3}$$

Where SD_x is the standard deviation of selection endpoints projected onto the vector between the two targets (i.e., the task axis). It incorporates the variability in selection coordinates and is multiplied by 4.133, which corresponds to ± 2.066 standard deviations from the mean. This effectively resizes targets so that 96% of selections hit the target, normalizing experimental error rate to 4%. This accuracy adjustment facilitates comparison of throughput scores between studies with varying error rates by first normalizing accuracy [51, 68].

2.5 Effects of Scale on Selection Performance

HCI scholars have previously studied both visual and motor scale in non-VR contexts, often using Fitts' law studies. Factors involved in evaluating scale include the physical dimension of the device screen, the pixel density of the screen, and the distance between the user and the display screen [2, 17, 22, 37, 47, 79].

Browning et al. found that physical screen dimensions affected target acquisition performance negatively, especially for smaller screens [17]. Chapuis et al. also report that target acquisition for small targets suffered, indicating that selection performance is

affected by movement scale, rather than visual scale [22]. Accot et al. used identical display conditions with varying input scale to isolate movement scaling to adjust the trackpad size systematically [2]. They used this set up with the steering task [3] and found a “U-shaped” performance curve, meaning that small and large trackpad sizes had the worst performance. They concluded that this was a result of human motor precision [2].

Kovacs et al. studied screen size independent of motor precision. Their findings suggested that human movement planning ability is affected by screen size [47]. Hourcade et al. showed that increasing the distance between the user and the screen, which causes the targets to scale due to perspective, affects accuracy and speed negatively as well [37].

2.6 Non-inferiority Testing

We end this review of background work by discussing non-inferiority statistical testing, which we employ in our analysis. Non-inferiority testing is a form of equivalence testing that shows if a condition is statistically *no worse* than another, in contrast to traditional null-hypothesis statistical testing, which can only reveal *differences* between conditions. It requires defining an indifference zone, i.e., the maximum allowed difference between two conditions to be considered non-inferior based on the context of the study [67].

With the indifference zone defined, we next analyze the mean difference between the conditions and the 1-tailed 95% confidence interval of that difference. Finally, we check if the mean difference score and the 1-tailed 95% confidence interval fall within the extents of the indifference zone. If so, then the two conditions are deemed to be no worse than each other, i.e., non-inferior [67]. Although this form of analysis is rare in HCI, it has been used before in the context of VR Fitts’ law experiments [44].

Chapter 3: Warped Virtual Surfaces Design and Implementation

With WVS, users perceive themselves interacting with an arbitrary sized virtual surface, that is potentially much larger than that physically available. The actual (i.e. real) interaction space or panel is always the same (e.g., the physical tracking area of the tablet or the real bounds of the panel). We rescale the virtual plane in VR that would typically represent a virtual screen with 1-to-1 mapping to the physical world (See Figure 3). We render targets on locations that would fall outside the bounds of the physical tablet’s tracking area or the real rectangular panel area.

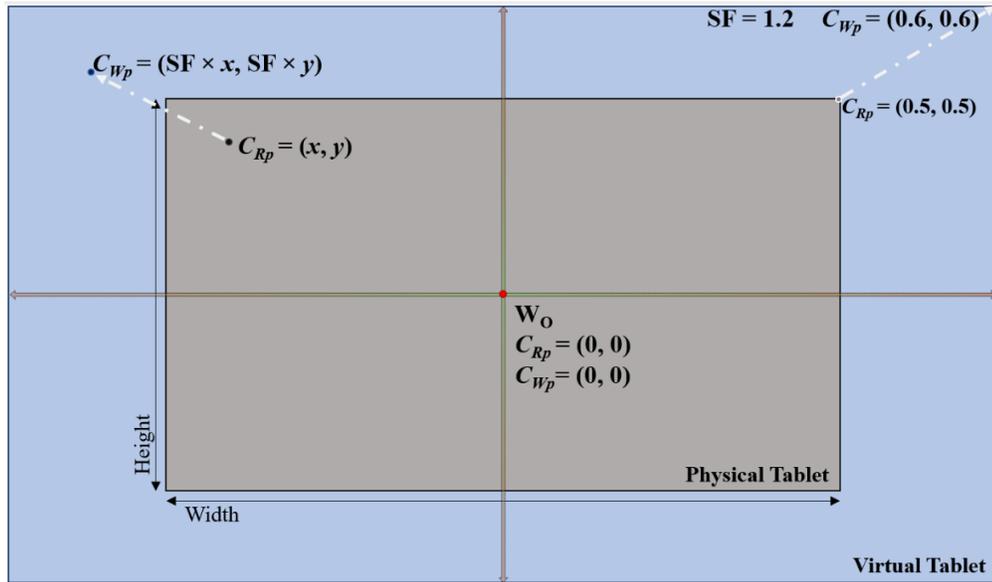


Figure 3: Visual representation of the WVS system.

For our first study, we used a tablet. Tablet drivers typically provide the stylus tip position on the tablet relative to the top or bottom left corner (i.e. the coordinate origin of the tracking area) with x and y values ranging from 0 to 1. In our case, the origin was the bottom left corner. The coordinate range is calculated based on the physical distance of the stylus tip to the coordinate origin and dividing the x and y values of that distance vector by the respective physical *width* and *height* of the panel or tablet’s rectangular active tracking

area. We calculate this as the real cursor position or real stylus tip position (C_{Rp}), i.e. the point where the stylus tip is physically touching the tablet or where the user is holding the stylus tip in 3D space:

$$C_{Rp} = (1/width, 1/height) \times dist(stylusTip, W_o) \text{ Equation 4}$$

We can use this equation for scenarios without a physical tablet or panel present or in 3D without any modifications. In the absence of a physical tablet or panel, *width* and *height* would represent the dimensions of the real rectangular panel area in 3D space seen in VR with 1-to-1 mapping (i.e., virtual panel without any scaling).

Similar to haptic retargeting, we used a warping origin (W_o) [6] for scaling. For WVS, the origin is the centre of the physical or real panel's rectangular area. We chose the centre of the panel as the warping origin because it was the point from around which the physical or real panel would grow in size. In other words, W_o is the only point on the panel or tablet surface, which, regardless of the SF, remains in its original 1-to-1 mapping position. In contrast, the tablet or panel corner points are subject to scaling. Therefore, we chose W_o as the origin point for both C_{Rp} and the virtual warped cursor position or the warped stylus tip position (C_{Wp}), i.e. the position of the cursor the user sees on the virtual screen panel or in the absence of a tablet, the 3D stylus position in VR.

For tablets, we shift the coordinate system origin of C_{Rp} from the bottom left corner of the tablet to W_o by shifting the output range of the C_{Rp} points to range from -0.5 to 0.5 instead of 0 to 1. This origin shift results in the centre of the tablet tracking surface to be represented as (0, 0) instead of (0.5, 0.5) by the software system. We tracked the stylus tip with the tablet's built-in digitizer and apply the SF only when the stylus is within tracking range to the tablet's surface, ensuring that warping is limited to the tablet's surface.

In the absence of a physical tablet or panel, we no longer shift the coordinate system origin. The coordinate origin shift is no longer required because we are working in 3D with a uniform tracking system for all 3D tracked devices. Hence, we can place a virtual panel (visible to the user in VR) in the VE and track the centre effortlessly. We used the local 2D coordinate system in the case of the tablet mostly for simplifying the calculations and the fact that we were using the tablet's digitizer to track the stylus tip pointing location on the tablet surface.

At W_O , C_{Rp} and C_{Wp} align. Warping the panel's surface causes C_{Wp} to move ahead of C_{Rp} as users move the stylus further away from W_O . C_{Wp} 's movement behaviour is similar to the effects of CD gain on traditional mouse cursor movement, where a small movement of the physical mouse translates to a large screen movement for the mouse cursor. We used a similar idea to extend the virtual cursor or stylus reach on the panel in VR with WVS. A larger SF would cause the C_{Wp} to speed up, much like a high CD gain. Figure 3 demonstrates the behaviour of WVS. C_{Rp} values multiplied by a Scale Factor yield C_{Wp} , which is where we render the VR cursor on the tablet.

$$C_{Wp} = \mathbf{ScaleFactor} \times C_{Rp} \quad \text{Equation 5}$$

In the case of 3D tracking and the absence of a tablet with a digitizer, we do not directly set the virtual position of the stylus in VR. We calculate the C_{Wp} in each frame and add an offset to C_{Rp} based on the difference between C_{Rp} and the calculated C_{Wp} based on Equation 5 in that frame.

Chapter 4: User Study 1-Effects of Surface Warping on Performance

We conducted a Fitts' law experiment comparing several SFs to a 1-to-1 mapping “*control condition*.” Our objective was to determine whether the application of scaling in our warped virtual surface technique influenced user performance in selection. We used a set of pre-selected amplitude and width pairs, rather than fully crossing a selection of amplitude and widths. This ensured that all combinations of A and W were reachable with the 1-to-1 mapping condition. Also, a sufficiently large W could yield targets that were cut off the virtual tablet screen, which would not be reachable by the cursor without warping. We thus carefully chose our amplitude and width pairs so that they would cover a wide range of IDs, while still having physically reachable targets under 1-to-1 mapping.

4.1 Hypothesis

Past studies suggest that although visual and motor scale affect selection performance differently, small scales and sizes impact user performance negatively for both [12, 17, 22, 25, 37, 54, 79]. Most similar to our work, Blanch et al.'s study revealed that pointing task performance is governed by motor space rather than visual, meaning selection performance depends on the physical selection and movement instead of the task users see themselves doing [12].

Thus, we hypothesize that movement time (MT), error rate, target entry count and throughput (TP) would be unaffected with varying SFs since participants are still selecting the same physical locations on the tablet's surface. In other words, we hypothesize that selection performance will be the same regardless of the influence of warping and SF. We show this by using a non-inferiority statistical analysis [67] (explained in 2.6).

4.2 Participants

We recruited 24 participants (11 females, aged 19 to 64, $\mu = 26.5$, $SD = 10.5$). Three were left-handed, and one was ambidextrous but chose to complete the experiment using their right hand. We also surveyed their experience with VR and games: 62.5% reported having *no* VR experience at all, 37.50% reported having *a little* VR experience, and 4.20% *a moderate amount*. In terms of gaming experience, 37.50% reported having *no* 3D First Person game experience, 20.80% reported having *a little*, 29.20% reported having *a moderate amount*, 12.50% reported having *a lot of experience*. Participants were free to decide qualitatively how much experience they had. All participants had *normal* or *corrected-to-normal* stereo vision, assessed based on questioning before entering VR.

4.3 Apparatus

This section provides the details of our experiment design. Figure 4 depicts our setup.

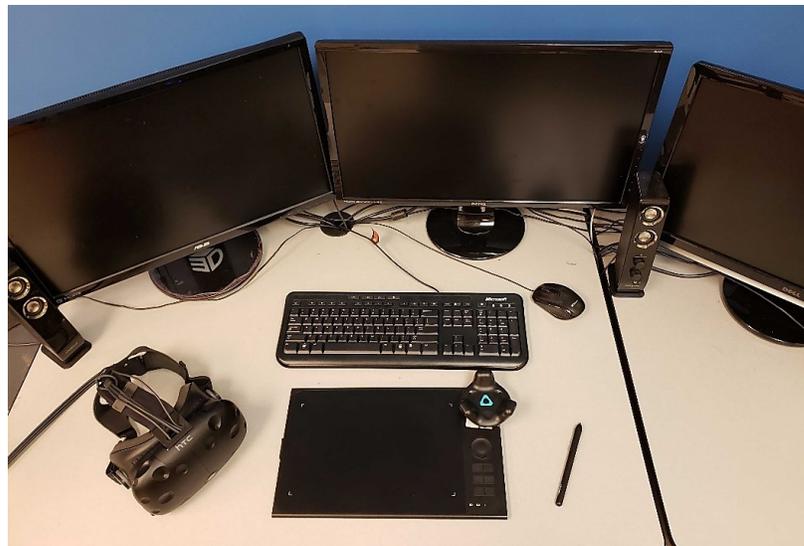


Figure 4: Table setup with hardware devices used in the experiment.

4.3.1 Hardware

We used a PC with an Intel Core i7 processor PC with an NVIDIA Geforce GTX 1080 graphics card. We used the HTC Vive VR platform, which includes an HMD with $1080 \times$

1200 pixel resolution per eye, 90 Hz Refresh Rate, and 110 degrees field of view. The tablet was an XP-PEN STAR 06 wireless drawing tablet. Its dimensions were 354 mm × 220 mm × 9.9 mm with a 254 mm × 152.4 mm active area, and a 5080 LPI resolution. The tablet includes a stylus with a barrel button and a tip switch to support activation upon pressing it against the tablet surface. The 2D location of the stylus is tracked along its surface by the built-in electromagnetic digitizer. We affixed a Vive tracker to the top-right corner of the tablet using Velcro tape, as seen in Figure 5.

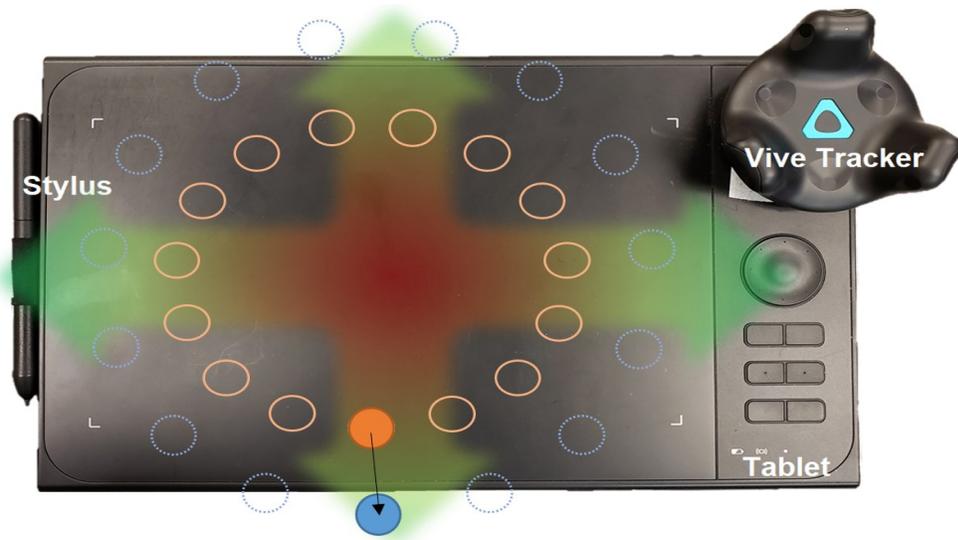


Figure 5: Overlay of Fitts' law task on the tablet. Orange circles depict the physical target location, while blue circles depict the targets the user saw in VR. Gradient arrows illustrate the surface warping effect and how the virtual surface grows in all directions.

4.3.2 Software

We developed our VR software using Unity3D 2019.2 and C# on Microsoft Windows 10. We used several assets from the Unity asset store to populate the VR environment seen in Figure 6. We used a modified version of the source code provided by Hansen et al. [28] to develop our experiment with Unity. The tablet was recognized as a human interaction device profile by Windows 10, causing the OS to map tablet input to the mouse cursor.



Figure 6: The virtual table where participants sat during the study.

Having the tablet input mapped to the mouse cursor was undesirable, so we used a custom *LibUSB* driver that allowed direct access to the tablet data to use within Unity's simulation environment. The library provided stylus coordinates on the tablet surface and whether the stylus was touching the tablet surface or hovering above it within an approximately 1 cm range. The software polled the Vive tracker to map a virtual panel to the physical tablet's active tracking area, co-locating the centre of the two. The virtual panel in VR had a resolution of 4000×2400 , with the same size in 1-to-1 mapping as the physical tracking area on the tablet. When scaling was applied, the virtual tablet panel size is multiplied by the SF value.

We could not find a reliable and suitable solution to externally track the stylus or hands while holding the stylus and using the tablet. Hence tracking was limited to the tip of the stylus in a close range to the tablet surface by the tablet's digitizer. Due to this limitation, we did not render a model of the stylus or hands. However, when the stylus was in the range of the tablet, we displayed a virtual star-shaped cursor with a dot hotspot in the centre at the stylus tip. By applying pressure and touching the tablet with the stylus,

input (“*click*”) events were detected by the system. The system also calculated the virtual cursor position on the virtual tablet surface used for selection based on the method described in Chapter 3.

The virtual tablet was positioned on a table, as seen in Figure 6. Figure 7 depicts the participants’ view in VR during a selection task. While hovering on targets, they changed colour to indicate which would be selected if the tip switch was pressed. Upon selecting a target successfully in this fashion, an auditory “*click*” sound was played, and the experiment would move to the next target in the sequence for selection. In case of an error, a distinct “*beep*” sound was used to indicate the error in the selection, and the experiment would move to the next target in the current sequence. The system did not register multiple input events in case users kept the stylus on the active area and applied pressure on the tip. For each selection, users had to raise stylus from the tablet surface and tap on the next target for the system to register a new input event.

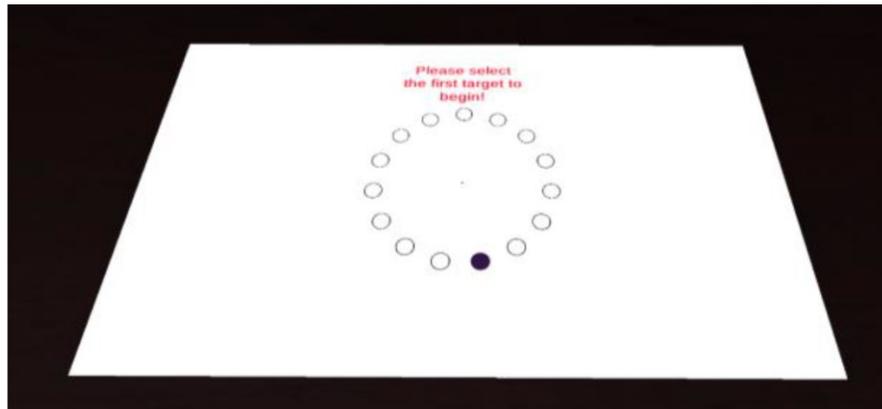


Figure 7: Fitts law task as seen in on the tablet in VR.

The software logged movement time, error rate, and calculated throughput, as described in Equation 2. It also recorded *target entry count*, i.e., the number of times the cursor entered each target before selection. The software also imposed an accuracy

requirement; if a participant missed more than 50% of the targets in a 15-target sequence, they had to repeat that entire sequence.

4.4 Procedure

Figure 8 shows a participant in the study. Overall, the experiment took about one hour, with participants in VR for ~45 to 50 minutes. Before starting, participants provided informed consent and completed a demographic questionnaire.

The main experiment was divided up into eight blocks (one per SF). Each block consisted of ten sequences, one for each of the 10 IDs used. In each sequence, participants were presented with 15 targets. The participant had to successfully select at least 50% of the 15 targets in order to move on to the next sequence. Participants were given an (at least) 30-second break between each block. During the break, they could remove the HMD if desired.

In order to begin each sequence, they had to select the first target to begin the timer. The first selection in each sequence was thus not logged as it just started the sequence. This target would be selected again as the last target in the sequence.



Figure 8: A participant in our experiment sitting behind a desk aligned with the virtual table in VR.

There was no training session before starting the experiment. The task involved selecting circular targets, as is commonly used in Fitts' law experiments (see Figure 2). The task required selecting the highlighted target as quickly and accurately as possible. If participants missed the target, the system would record an error and move on to the next target. If the participants had more than 50% error rate, they were asked to redo the sequence, the data logging system would record this.

After completing the experiment, the participants exited the VE and completed a post-questionnaire where they gave comments on their experience using the VR tablet prototype. They were then debriefed and compensated \$10 CAD.

4.5 Experiment Design

Our experiment employed a within-subjects design with two independent variables Scale Factor and ID (index of difficulty):

Scale Factor (SF): 1, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4.

ID: 1.1, 1.5, 1.8, 2.1, 2.3, 2.7, 3.5, 3.8, 4.0, 4.6.

The ID values were generated from the following 10 combinations of A and W (in pixels):

<i>ID</i>	1.1	1.5	1.8	2.1	2.3	2.7	3.5	3.8	4.0	4.6
<i>A</i>	300	450	1300	1600	800	1100	1000	2000	2250	2300
<i>W</i>	250	250	500	500	200	200	100	150	150	100

Table 2: Amplitude and Width pairs with their respective Index of Difficulty.

The SFs were applied to both the cursor position and virtual panel size in VR, as described in Chapter 3. IDs were calculated according to Equation 1 using the SF of 1 (i.e., 1-to-1 mapping). SF ordering was counterbalanced according to a balanced Latin squared.

Within each SF, ID order was randomized, with one ID per sequence (i.e., circle) of 15 targets.

Our dependent variables included:

- **Movement time:** the average selection time, in milliseconds.
- **Error rate:** the average proportion of targets missed (as a percent).
- **Throughput** (in bits per second, bps): calculated according to the *ISO 9241-9* standard and based on Equation 2 [27, 30, 51, 68, 74].
- **Target entry count:** number of times the cursor entered a target prior to selection.

Higher target entries may indicate some control problems [53].

Like other scholars [27, 51, 52, 68, 75], we argue that throughput gives a better idea of selection performance than either movement time or error rate. The accuracy adjustment used to derive throughput incorporates speed and accuracy together, making throughput constant regardless of participant biases towards speed or accuracy. It is thus better facilitates comparison between studies and is more representative of performance than speed or accuracy alone [52]. We use it as our primary dependent variable, similar to other studies. In total, participants each completed 8 SFs \times 10 IDs \times 15 trials (i.e., individual target selections) for 1200 selections in total. Our analysis is thus based on 24 participants \times 1200 trials = 28800 selections in total.

4.6 Results

We used repeated-measures ANOVA on movement time, error rate, throughput, and target entries to detect significant differences due to SF. We did not analyze ID, as it is expected to yield performance differences. As detailed below, we found significant main effects for

SF only for MT and target entries. We did not find significant differences in error rate, and most importantly, for throughput. Horizontal bars (•••••) indicate significant pairwise differences with Bonferroni adjustments.

We note here that while standard null-hypothesis statistical testing will determine if two conditions are significantly *different*, our objective was to determine if WVS is *not worse* than the one-to-one mapping (i.e., SF of 1). This would suggest that it has minimal impact on user performance and is thus a viable technique for virtually extending tablet surfaces. However, standard null-hypothesis statistical tests (e.g., ANOVA) do not determine if two conditions are statistically *the same* or *non-inferior* compared to one another. Hence, we instead conducted non-inferiority testing for TP and error rate [67]. For throughput, we used the same indifference zone (1 bps) as Kohli et al. [44]. For error rate, they used the smallest unit of error, i.e., one target miss in a sequence. We used the same threshold, in our case, one miss in fifteen targets, for a 6.66% indifference zone.

4.6.1 Throughput

RM-ANOVA on throughput revealed no significant difference for scale factor ($F_{4,21, 96.98} = .92, ns$). Mean TP was fairly consistent across all scale factors. See Figure 9.

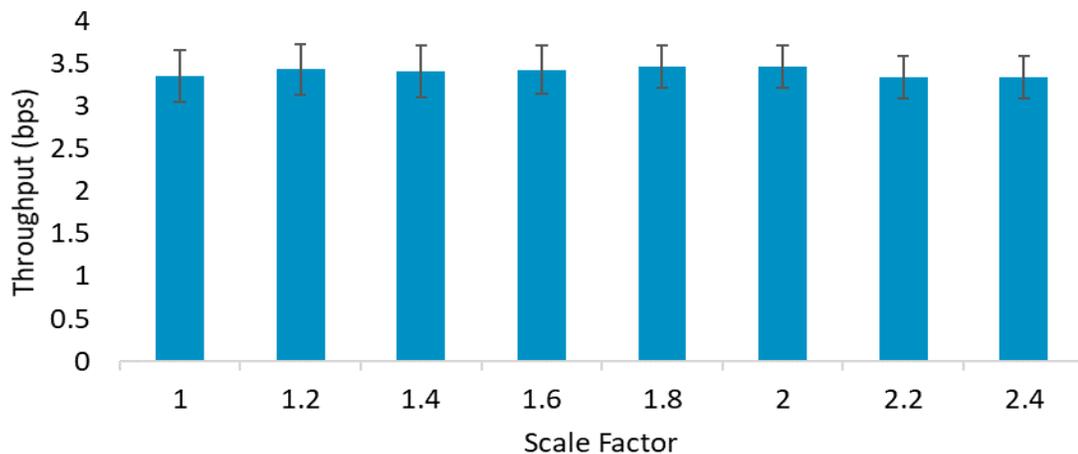


Figure 9: Mean TP for each SF value. Error bars indicate 95% CI.

To determine if throughput is statistically consistent across SFs, we conducted our non-inferiority test (See 2.6). With the aforementioned indifference zone of 1 bps, the mean difference between each compared SF and the lower bound of the one-tailed confidence intervals should be greater than -1 bps to be considered non-inferior. Table 3 shows the results of the non-inferiority test for pair-wise comparisons (with Bonferroni corrections) between the 1-to-1 mapping and all other SFs.

Based on this analysis, no SF has worse TP than 1-to-1 mapping (i.e., they are all considered non-inferior). Overall, this result indicates that throughput is not affected by scale factor, in line with our hypothesis and suggests the WVS technique has minimal impact on user performance.

SF Pairs	Mean Diff.	1-tailed 95% conf. Interval	SD Error	Non-inferiority Comparison
1-1.2	-0.077	> -0.313	0.067	-0.313 > -1.0
1-1.4	-0.059	> -0.333	0.078	-0.333 > -1.0
1-1.6	-0.073	> -0.426	0.100	-0.426 > -1.0
1-1.8	-0.115	> -0.393	0.079	-0.393 > -1.0
1-2.0	-0.108	> -0.410	0.086	-0.410 > -1.0
1-2.2	0.0130	> -0.260	0.077	-0.260 > -1.0
1-2.4	0.0190	> -0.194	0.060	-0.194 > -1.0

Table 3: Mean TP differences and non-inferiority test results.

4.6.2 Error Rate

We found no significant difference in error rate for different SFs ($F_{3,98, 91.56} = 2.07, p > .05$). Based on Figure 10, they are reasonably consistent across the eight scale factors. Like with throughput, we used a non-inferiority test on error rate to determine if each SF yielded error rates no worse than the 1-to-1 SF. Using the aforementioned indifference zone limit of 6.66%, each SF must have error rate differences no higher than 6.66% compared to the SF of 1 (i.e., 1-to-1 mapping).

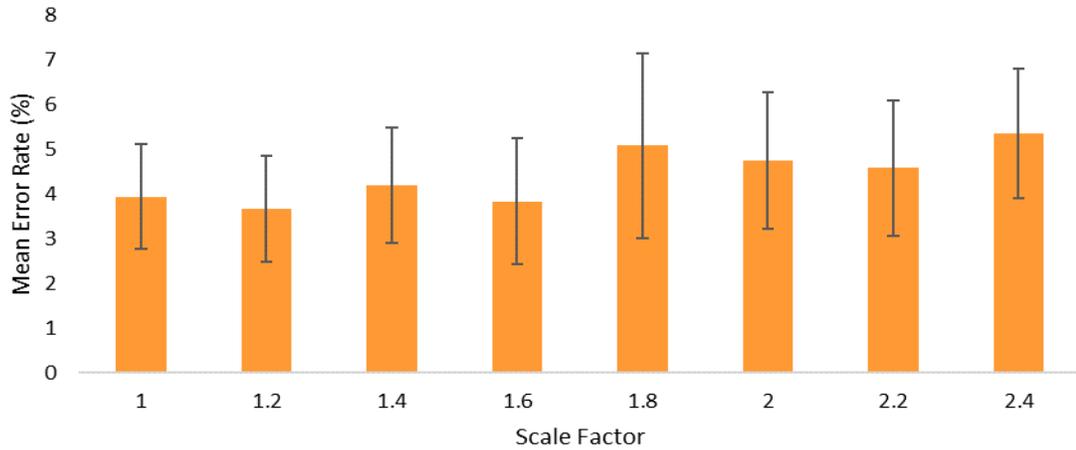


Figure 10: Mean error rate in different SF conditions. Error bars indicate 95% CI.

The results of this analysis, with Bonferroni corrections, are seen in Table 4. According to these results, no SF offered a worse error rate than the SF of 1. Results indicate that the error rate was also unaffected by SF value, also in line with our hypothesis, meaning target misses rates were constant regardless of SF.

SF Pairs	Mean Diff.	1-tailed 95% conf. Interval	SD Error	Non-inferiority Comparison
1-1.2	0.278	< 1.708	0.405	1.708 < 6.66
1-1.4	-0.25	< 1.671	0.544	1.671 < 6.66
1-1.6	0.111	< 2.572	0.697	2.572 < 6.66
1-1.8	-1.139	< 1.636	0.786	1.636 < 6.66
1-2.0	-0.806	< 1.213	0.572	1.213 < 6.66
1-2.2	-0.639	< 1.595	0.633	1.595 < 6.66
1-2.4	-1.417	< 0.189	0.455	0.189 < 6.66

Table 4: Mean error rate differences and non-inferiority test results.

4.6.3 Movement Time

RM-ANOVA resulted in significant results in the case of movement time. We also note that as suggested by Kohli et al.[44], it is not clear what a reasonable indifference zone for movement time should be.

Mauchly's test revealed that the assumption of sphericity was violated ($\chi^2(27) = 51.33, p = .004$) so we applied Greenhouse-Geisser correction ($\epsilon = .56$). There was a

significant main effect of scale factor on movement time ($F_{3,98, 91.65} = 13.92, p < .001, \eta_p^2 = .37, \text{power} = 1.00 (\alpha = .05)$).

Post-hoc pairwise differences test results and mean MT scores are seen in Figure 11. Results indicate that higher SF values resulted in higher mean movement time, suggesting participants moved slower with higher SFs. Our hypothesis failed in the case of movement time.

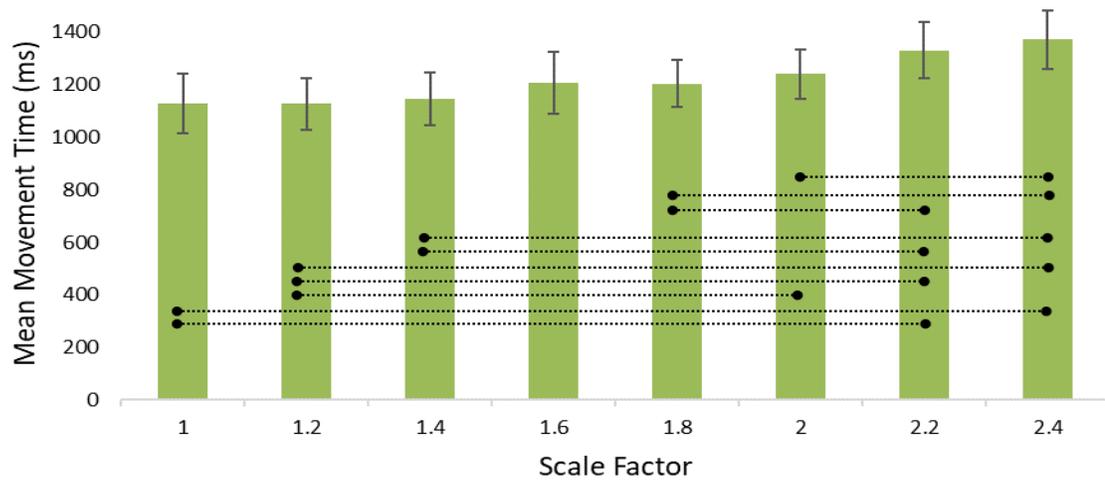


Figure 11: Mean MT in different SFs. Error bars show 95% CI.

4.6.4 Target Entry Count

As seen in Figure 12, higher SFs yield slightly higher target entry counts, suggesting participants had more difficulty getting the cursor into the target before selection. The assumption of sphericity was not violated, so results were analyzed without any corrections applied to degrees of freedom.

There was a significant main effect of SF on target entry count ($F_{7, 161} = 17.41, p < .001, \eta_p^2 = .43, \text{power} = 1.00 (\alpha = .05)$). Higher SF resulted in average higher target re-entries for correct selection. Our hypothesis failed for the target entry count.

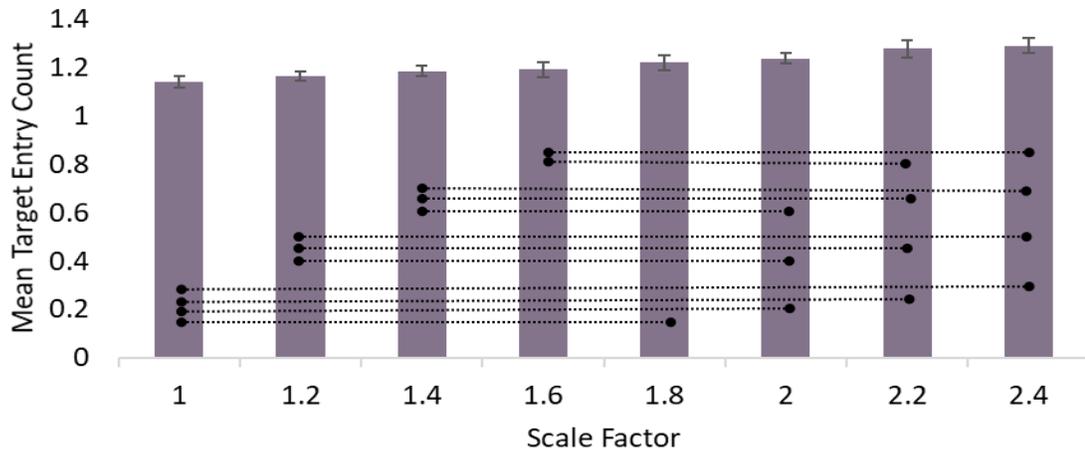


Figure 12: Mean Target Entry count for each SF. Error bars show 95% CI.

Several participants mentioned having difficulty selecting the smallest targets. As a result, we also analyzed if the target entry count was affected by the target size using. The assumption of sphericity was not violated, as indicated by Mauchly's test.

We found a significant main effect of target width on target entry count ($F_{4, 92} = 13.52, p < .001, \eta_p^2 = .37, \text{power} = 1.00 (\alpha = .05)$). Figure 13 depicts mean target entry count for different target widths. Our analysis did not find a significant interaction effect between SF and target width ($F_{28, 644} = 1.33, p > .05$). Results suggest smaller targets were harder to hit upon initial entry and required on average more re-entries to select.

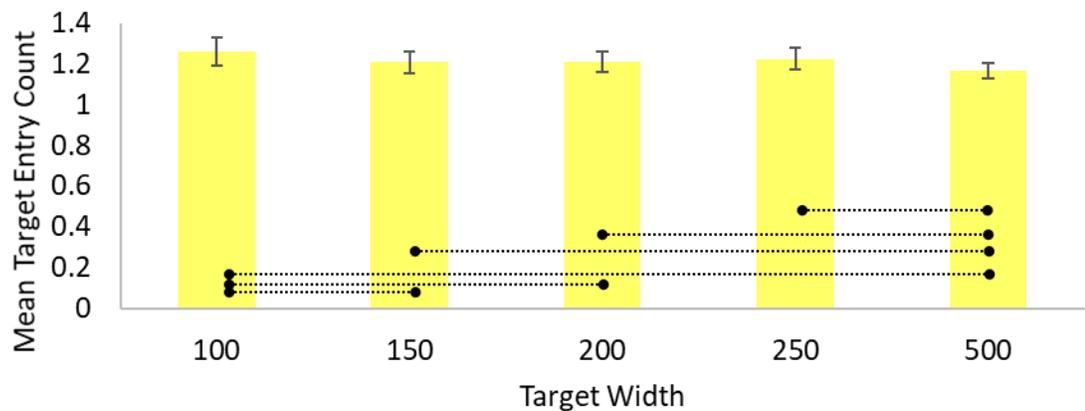


Figure 13: Mean target entry count across target width. Error bars show 95% CI.

4.6.5 Fitts' Law Analysis

Fitts' law is commonly used as a predictive model of movement time. We conducted this analysis by performing a linear regression of MT onto ID. Figure 14 depicts the relationship between MT and the ID values we used in our experiment.

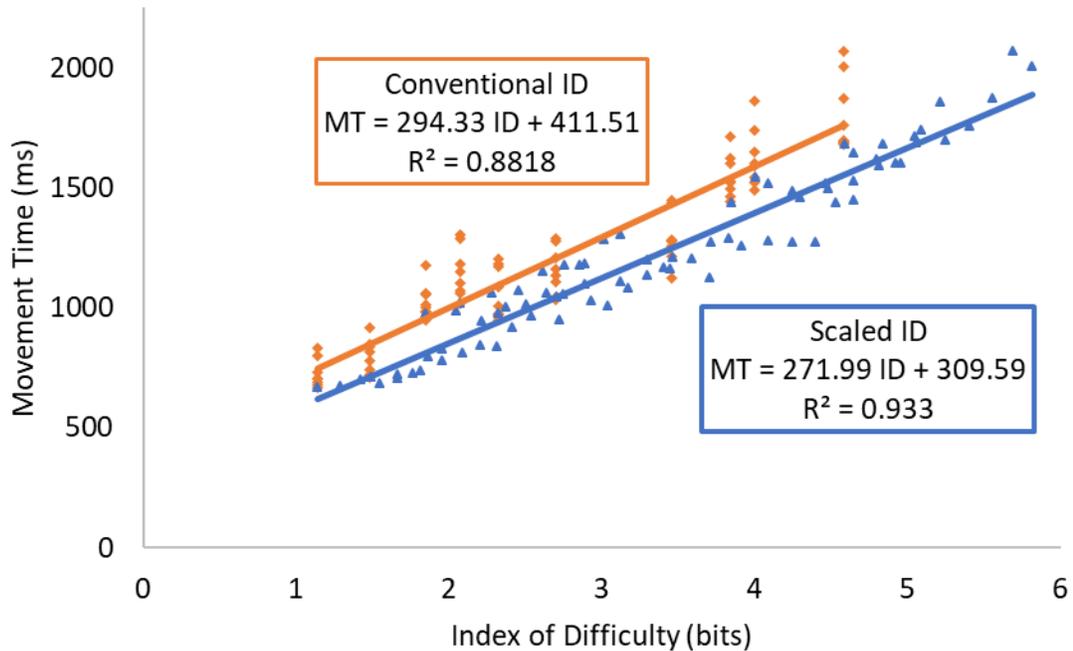


Figure 14: Linear regression of MT on ID for both conventional (i.e., presented) ID and scaled ID (applying the scale factor to A when calculating ID).

As is often the case in Fitts' law studies, there is a strong linear relationship between MT and ID. We performed linear regression for both conventional ID (i.e., the 10 IDs listed in Table 2), and for scaled ID. Scaled ID was calculated based on the SF value applied to target amplitudes when calculating ID. Applying the scale factor in this way is more representative of the task participants perceived themselves as performing. Interestingly, the Fitts' law regression using scaled ID yielded a better fitting model.

4.6.6 Effective Width Analysis

To further explore why throughput was constant, despite increasing movement time across scale factors, we also analyzed effective width (W_e). We note that throughput is based on effective width, which in turn relates to the magnitude of errors, rather than the error rate. This explains how throughput can stay constant across SFs while why movement time significantly increases with SF (and while error rate is also constant).

Misses farther from the target will increase effective width values, while selections closer to the target centre (i.e. more accurate selection) will decrease it. Thus, we looked into how mean W_e changed under different SF conditions. Based on Figure 15, W_e appears to decrease with higher SFs. This indicates that participants were making more accurate selections with higher SFs, likely yielding the higher movement times noted above with higher SFs.

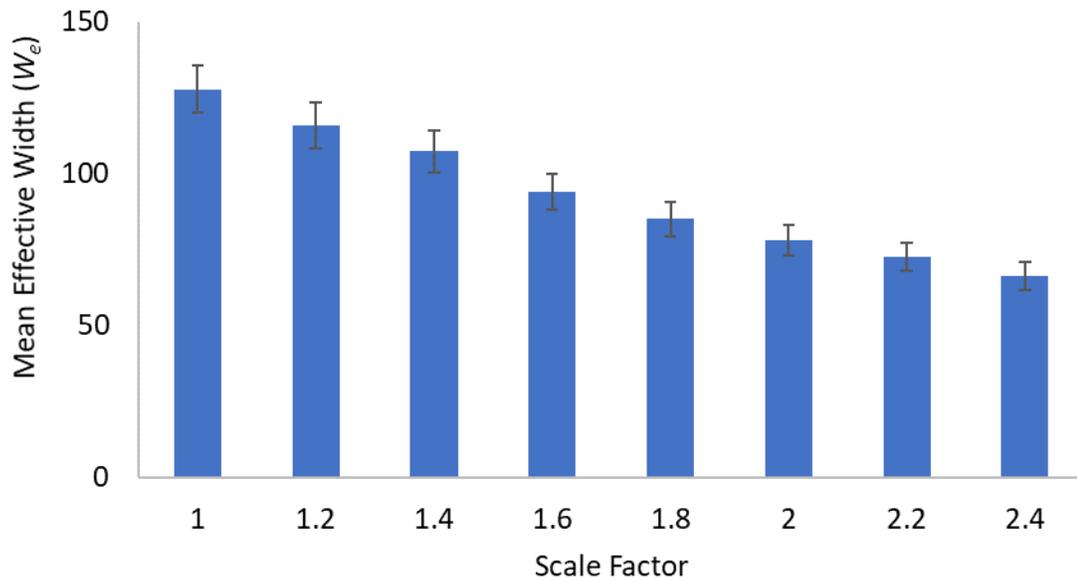


Figure 15: Mean W_e for different SFs in our experiment. Error bars show 95% CI.

4.6.7 Post-Questionnaire

We used the device assessment questionnaire provided by *ISO 9241-9* [27] to evaluate fatigue, accuracy and the overall experience of using table and stylus input method with WVS. Participants had to rate each phrase from 1 (*lowest*) to 5 (*highest*). See Figure 16. We did not compare results across different SFs since participants were unlikely to notice differences in the SFs, and this would require they complete eight lengthy questionnaires instead of just one.

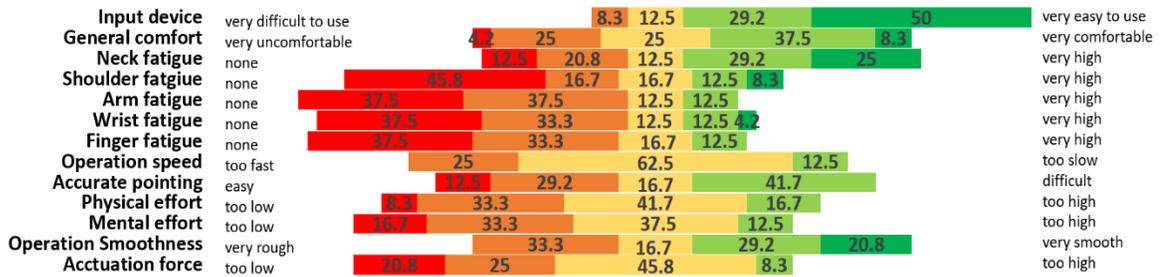


Figure 16: Device Assessment Questionnaire. Label numbers indicate the percentage of participants choosing each answer.

4.7 Discussion

Results indicate that WVS had significant effects only on MT and target entry count. Notably, the largest SFs were significantly different. For error rate and TP, non-inferiority testing indicated that WVS is no worse than 1-to-1 mapping. Target entry count was affected by the target size, which was unsurprising, but highlights some difficulty in accurately selecting the smallest targets.

4.7.1 General Discussion

Our results are in line with past work and suffer from some of the same limitations [12, 44]. The most important result from our study is that throughput is relatively stable when using WVS, especially for modest scale factors, e.g., 1.2, 1.4 and 1.6. One explanation could be that the same muscles are used across all selections under different SFs. Pointing

performance is known to be affected by the muscle used to reach the target [83]. This is a promising finding, as it suggests that WVS can be applied in tablet-based VR to provide a larger virtual tactile proxy than is otherwise available. Similarly, as indicated in our results, movement time is significantly (if only slightly) worse with higher SFs, especially at 2.2 and 2.4.

Overall, our results show lower throughput with a tracked stylus compared to redirected touching [44]. Lower throughput and error rate and higher movement time in our study are potentially due to the different warping techniques we used. Other factors that could contribute to this difference are the different hardware setup, for instance, input using a stylus rather than fingers, and the position/orientation of the tablet in our study. Notably, our throughput scores – regardless of scale factor – are in line with previous work using a 3D tracked stylus, which is a closer comparison point [75]. Also, the tablet placed on the table caused participants to experience some neck fatigue, as indicated in the post-questionnaire results (see Figure 16) and participant comments. 54.2% of the participants reported high neck fatigue. Our participants also noted it was hard for them to select the smaller targets. One commented, “*There were sometimes where selecting the smaller circles was difficult.*” Such comments were not unexpected and are supported by the significant differences found in our analysis, as shown in Figure 13. One other contributor to this difficulty could be the limited screen resolution in the Vive HMD.

Higher scale factors yielded slightly higher movement times and target entries than lower scale factors. A potential reason for this is the increase in virtual cursor movement speed caused by scaling. This increase in cursor speed would make fast, accurate movement more challenging, particularly in precisely selecting targets. This kind of effect

has been noted before as a “U-shaped” curve for coarse/fine positioning times under different CD gain levels [2]. Also, since users were not able to see the stylus in VR, they likely moved more slowly to keep track of the cursor.

On the other hand, as seen in Figure 9, throughput is almost flat across scale factors. Throughput characterizes the speed/accuracy trade-off in selection tasks. For throughput to be flat across scale factors, and in light of increasing movement times, accuracy must have been better with higher scale factors. In our error rate analysis, we found non-inferiority between the 1-to-1 mapping and all other scale factors, suggesting error rates were at least not worse with higher scale factors. However, effective width (from which throughput is derived) is not based on error rate, but rather on the distribution of selection coordinates. In other words, the distance of the selection coordinates to the target centre influences W_e . Participants may miss targets at about the same rate but miss “*closer*” to the target (which yields lower W_e). Alternatively, they may hit closer to the centre of the target (which also yields lower W_e). This confirmed in our W_e analysis (see 4.6.6) – W_e became smaller with higher scale factors, which is why throughput was constant regardless of the SF. With higher SF, the cursor moved faster. Participants likely slowed their operation speed slightly to compensate for the higher cursor speed. This is reflected in higher MT for higher scale factors (Figure 11). By compensating (i.e., slowing down), participants were more readily able to precisely select targets (yielding lower magnitude misses, or selections closer to the target centre), resulting in lower W_e and higher TP.

Based on our observations, most target misses were due to loss of tracking for the stylus and participant moving their hand closer to regain tracking and accidentally touching the tracking surface. Some participants also commented on this. A participant reported:

“my errors were false selection during dragging my hand to the desired point.” Also, since we were warping the virtual space, moving the stylus even slightly could cause the virtual cursor to move outside smaller targets (increasing target entry count). Participants held the stylus at an acute angle relative to the tablet surface, instead of perpendicular to it; reaching and selecting smaller targets from the hovering state could cause the virtual warped cursor to fall outside the target even with slight movements in either direction. Participants also held the stylus differently, i.e., in a different position and with different gestures.

Participants found WVS easy to use, despite 41.7% finding accurate pointing difficult. One participant reported: *“Overall was easy to select the targets.”* Another mentioned that *“...would use again. Was more usable when the in-world representation of the tablet was larger, but it was still easy to select small targets on the small display.”* Half of our 24 participants reported the device to be very easy to use (Figure 16).

Based on comments, participants liked that they could use a larger touch surface in VR despite arm, wrist and finger fatigue, as indicated in Figure 16. One participant commented that *“I really like the idea of using smaller physical screens to choose on larger area in VR, hope it will become common input option for VR.”* Only three out of 24 participants reported they did not notice any change in their cursor movement speed while in VR. One person mentioned that *“I was able to observe the warping but not able to compare it to earlier trials. It was a smooth experience.”*

4.7.2 Limitations

The main limitation of our study is the indifference zones used for the non-inferiority analysis. More studies are required to determine valid indifference zones for performance in Fitts' law studies. In the presented work, we used the same indifference zones as Kohli

et al. [44] for the sake of consistency and to facilitate comparison. As mentioned in their work, some previous studies have found significant differences between conditions within the chosen indifference zones. Although we demonstrated non-inferiority, different indifference zones or statistical analysis could yield different results. Another limitation is that our hardware setup did not support 6DOF stylus tracking. One final limitation is that we did not compare our questionnaire results across different SFs. Our alternative was handing participants a questionnaire for each SF; however, we chose not to do this to keep the study under an hour. Also, our main independent variable was the scale factor and we were more interested in its effects on selection performance. Additionally, we did not tell participants about applying a scale factor and we thought asking them about scale factors and comparing them might get confusing. We believe our findings can still be useful and can help VR researchers and system designers.

4.8 Conclusion

In this study, we introduced Warped Virtual Surfaces, a technique to scale input space with a tracked tablet, yielding larger virtual tablets than that physically available. We evaluated the effects of surface warping on task performance using a tablet and stylus in VR. In terms of TP and error rate, WVS yielded consistent performance regardless of SF. Non-inferiority statistical tests showed that TP and error rates were statistically similar between all tested SFs and the “control” condition, i.e., the 1-to-1 mapping. However, for movement time and target entry count, we found small but significant differences, particularly for larger SFs, in line with previous work [12, 44].

Chapter 5: User Study 2–WVS Without Tactile Physical Panels

We conducted another Fitts' law experiment comparing several SFs to a 1-to-1 mapping “control condition.” The key difference between this and the previous experiment was that this experiment did not employ a tactile physical panel and instead used a 3D tracked stylus, as seen in Figure 17. Our objective this time was to determine how WVS would affect user selection performance without using a physical panel and with 3D stylus tracking. Using a 3D tracked input device in 6DOF would make the WVS technique more similar to Azmandian et al.'s Haptic Retargeting [6] and their proposed body warping technique. Employing 3D tracking also brings WVS to a more natural comparison point for classic 3D selection performance and manipulation tasks in current real-world applications, and in VR alike, as most VR systems do not employ tracked tablets, and instead rely on in-air interactions.

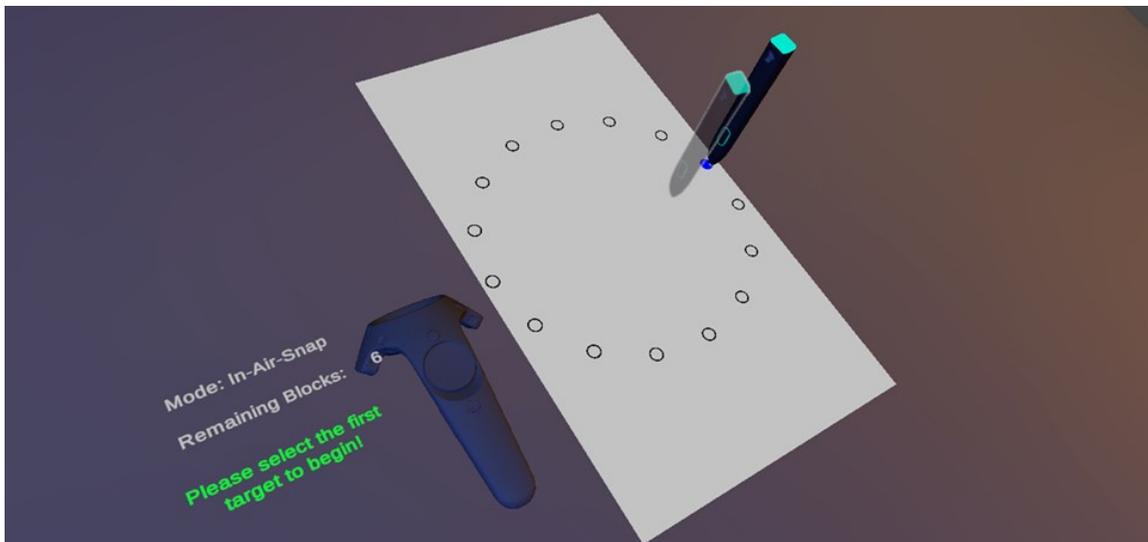


Figure 17: Depiction of WVS in 3D. The transparent stylus depicts the physical position of the stylus, while the opaque stylus depicts the position of the stylus as perceived by the user in VR.

We chose 10cm and 15cm (average size of a smartphone) as the *width* and *height* for the panel with 1-to 1 mapping, used in Equation 4 to calculate the virtual stylus position.

The virtual panel shown to the users in VR was 50cm × 75cm. For this experiment, we decided to keep our experiment design simple. Since we switched to 3D tracking, we kept the virtual panel size constant in this experiment (i.e. we did not scale up the virtual panel). We changed only the SF values that affected the stylus movement since we were more interested in the effects of SF on selection performance. We again chose the centre of the virtual panel as warping origin, i.e. where the virtual and real stylus align (See Chapter 3).

5.1 Hypothesis

Based on the results of our previous study, we hypothesize that movement time (MT), error rate, target entry count and throughput (TP) would be unaffected with varying SFs and a smaller real panel. In other words, we expect WVS not to affect user selection performance with a 3D tracked stylus and a smaller real panel without tactile or haptic feedback with a scale factor compared to 1-to-1 mapping, i.e. no warping.

5.2 Participants

We recruited 12 participants (5 females, aged 25 to 40, $\mu = 30.41$, $SD = 5.55$). Due to the on-going COVID-19 pandemic, participants either were recruited remotely (in the case of users who already had all requisite equipment), or we dropped the equipment off to local participants and remotely guided them through the study. In total, there were three remote participants and nine local participants.

All participants were right-handed. We surveyed their experience with VR and games: 16.7% reported having *no* VR experience at all, 58.3% reported having *a little* VR experience, 16.7% *a lot* and 8.3% *A great deal*. In terms of gaming experience, 8.3% reported having *no* 3D First Person game experience, 58.3% reported having *a little*, 8.3% reported having *a moderate amount*, 16.7% reported having *a lot of experience*, 8.3% *A*

great deal. Participants were free to decide qualitatively how much experience they had. All participants had *normal* or *corrected-to-normal* stereo vision, assessed based on questioning during recruitment. Figure 18 depicts a participant during the study.



Figure 18: A participant using the local setup.

5.3 Apparatus

With 3D tracking, if users moved beyond the boundaries of the defined *height* and *width* in Equation 4 (i.e. the size of the real rectangular panel area with 1-to-1 mapping), warping would still apply to the stylus position. This would result in the stylus to move further away from the warping origin as users can move the stylus freely in 3D compared to the limited 2D tracking in our first study (tracking was lost if users moved beyond the tracking range of the tablet). Warping is still only applied in the 2D plane of the virtual panel, i.e., we did not apply warping on stylus movements in the “up” or “down” directions (relative to the plane of the virtual panel).

5.3.1 Hardware

Local participants used a PC with an Intel *Core i7* processor with an NVIDIA *Geforce GTX 1080* graphics card. Remote participants used a VR-ready PC with at least an Intel *Core i5* or AMD *FX* processor, NVIDIA *Geforce GTX 970* or AMD *Radeon R9* graphics card with a Logitech VR Ink of their own. All participants used a Vive Pro with 1440×1600 pixels per eye, and 90HZ refresh rate for the screens inside the HMD with 110 degrees field of view. For local participants, we delivered the equipment (i.e. VR ready PC, Vive Pro and Logitech VR Ink) to them, while remote participants used their own Vive Pro device.

We used Logitech VR Ink as our stylus and the Vive controller (See Figure 19). Logitech VR Ink offers 3D tracking compatible with the Vive Base Stations 2.0 and uses the SteamVR platform¹⁰. The stylus supports most of the capabilities of VR controllers, such as different types of buttons (e.g. grip buttons and a touch strip button) as well as support for haptics by employing small vibrations.



Figure 19: HTC Vive Pro hardware and Logitech VR Ink stylus and the stylus button descriptions¹¹

¹⁰ <https://store.steampowered.com/app/250820/SteamVR/>

¹¹ https://github.com/Logitech/vr_ink_sdk/tree/master/Assets

5.3.2 Software

We repurposed our software from the previous study. We employed Unity 2019.4 and C# on Microsoft Windows 10. We used assets and drivers provided by Logitech¹² to create our software and create our virtual experiment environment, as seen in Figure 20. The software logged movement time, error rate, target entry count, and calculated throughput, as described in Equation 2. The software also imposed an accuracy requirement; if a participant missed more than 50% of the targets in a 15-target sequence, they had to repeat that entire sequence. This was intended to help manage the speed-accuracy trade-off.

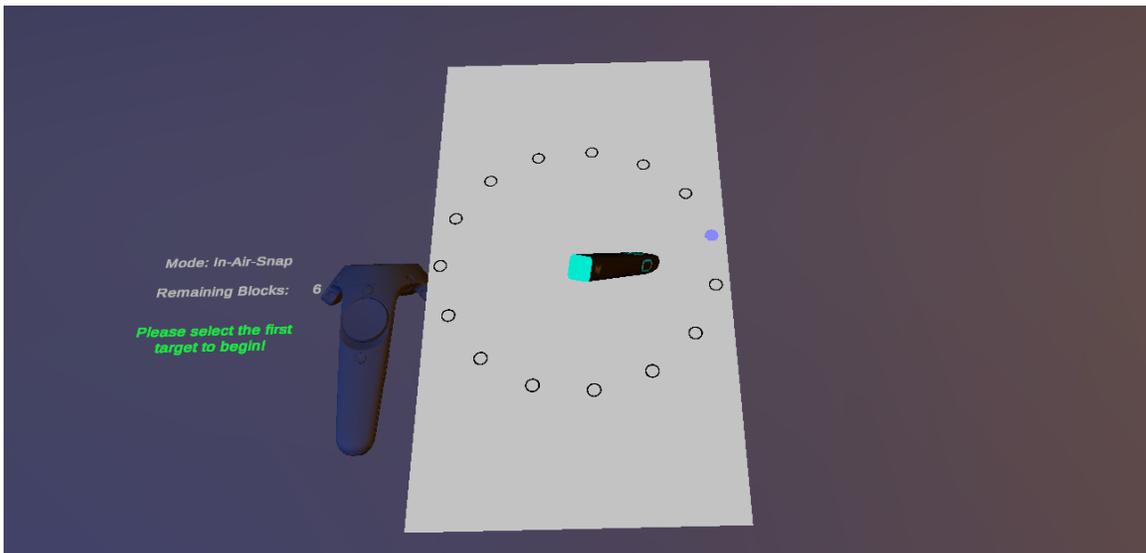


Figure 20: View of the selection task on the virtual panel in VR, as seen by participants.

To facilitate the remote experiments, the software automatically proceeded through the conditions and assigned the correct counterbalanced condition order based on participant ID number. Participants could take a quick break before starting each sequence of trials or targets if they desired. The software would not start logging unless participants selected the first target in each sequence. After going through all the conditions of the

¹² https://github.com/Logitech/vr_ink_sdk

study, the software would present users with a “thank you” message and exit to desktop automatically after several seconds. Overall, we reused most of the source-code from our previous study. We made minor changes to support 3D tracking of the VR Ink pen and to support better automation in the experiment steps by providing directions and messages to the participants.

The virtual panel was 50cm × 75cm with a resolution of 1080 × 1920 pixels. The panel was attached to the Vive controller and would move with the controller, as seen in Figure 20. Participants had to push the *Touchstrip* button on the Logitech stylus to trigger selection events (see Figure 19). Holding down the button did not result in successive selection events. Targets would change colour once the tip of the stylus entered the targets. Upon successfully selecting the targets with the *Touchstrip* button, an auditory “click” sound was used to indicate correct selection. In the case of an error in the selection, a “beep” sound would indicate missing the target. Participants could see which interaction mode they were currently using and how many more blocks were left for each condition (see Figure 20).

The stylus had two modes for interaction with the virtual panel:

- **Snap:** The stylus would snap to the virtual panel and vibrate upon contact (See Figure 21). Snapping prevented the virtual stylus from passing through the panel. We chose Snap as an “in-between” pseudo-haptic condition since we wanted to bridge the gap between our two studies as much as possible.
- **No-Snap:** The stylus would not snap to the virtual panel (without vibration) and pass through the virtual panel. No-Snap necessitated greater precision on the part of the user.

It is the classic VR interaction condition in our experiment, i.e., in-air spatial interaction with no tactile feedback necessitating some level of precision in depth.

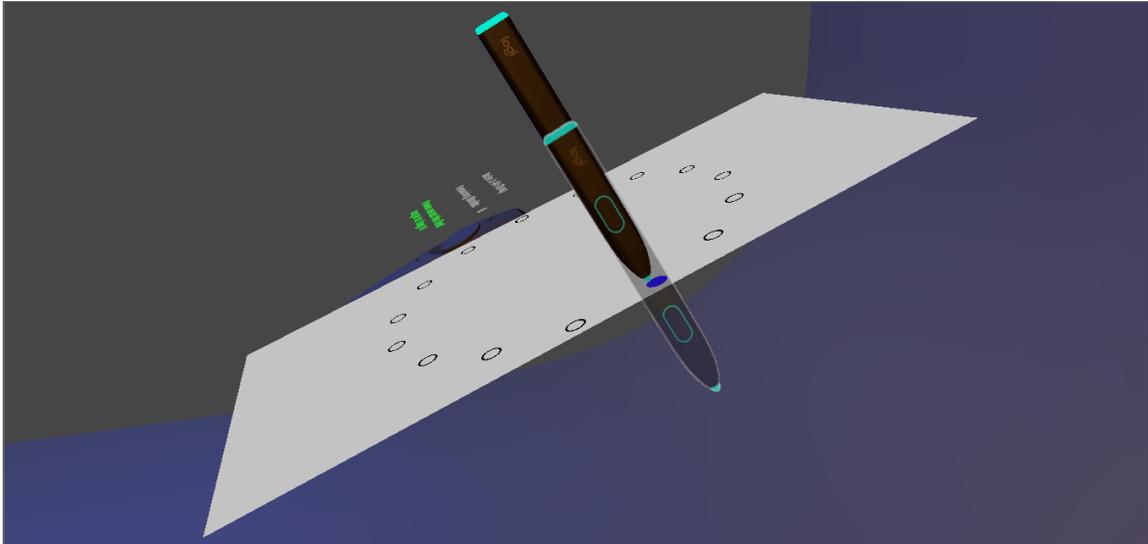


Figure 21: The transparent stylus is the stylus location without snapping enabled.

Participants had to enter their identification number before starting the experiment by selecting numbers on a keypad attached to the Vive controller with the stylus tip and pressing the *Touchstrip* button. This served the role of a practice round for participants to get them comfortable with VR and using the stylus and the Vive controller. See Figure 22.

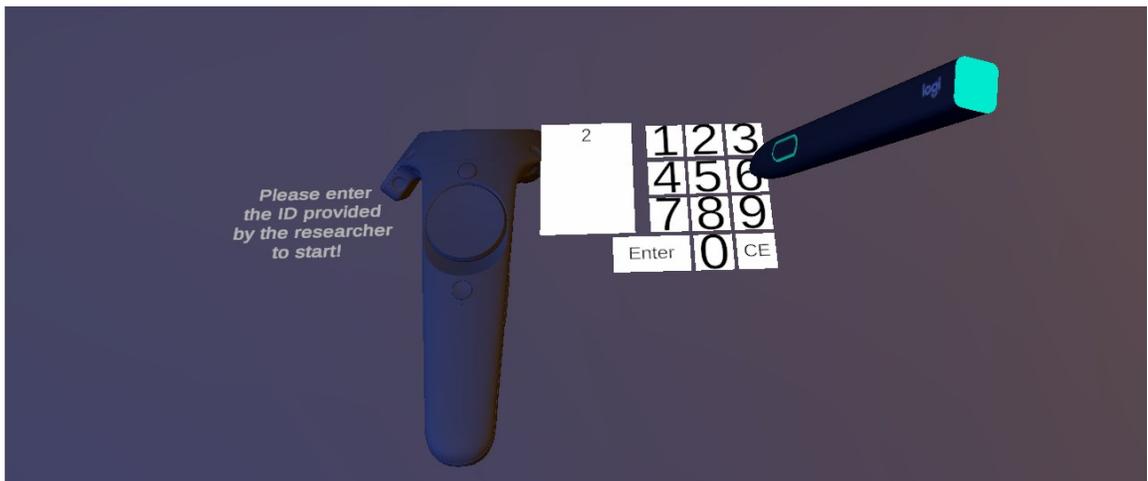


Figure 22: View of a participant as seen in VR while entering their ID number.

5.4 Procedure

The experiment was done remotely due to the COVID-19 global pandemic rendering in-person studies impossible. We either dropped-off the equipment for participants or participants already had a VR-ready PC and the Logitech VR Ink stylus. We dropped-off the disinfected VR equipment and PC at the participants' door and we took measures to ensure privacy and COVID-19 safety. We did not permanently store the participants' home addresses and contact information.

To ensure comparable setups across participants, we provided an instruction sheet that included guidelines on how to set up Vive Base Stations optimized for higher tracking quality for Logitech VR Ink (see Figure 23). The instructions also included information on how to use and set up the VR equipment with the PC. We also did video calls in case participants required extra assistance or had any questions during the study.

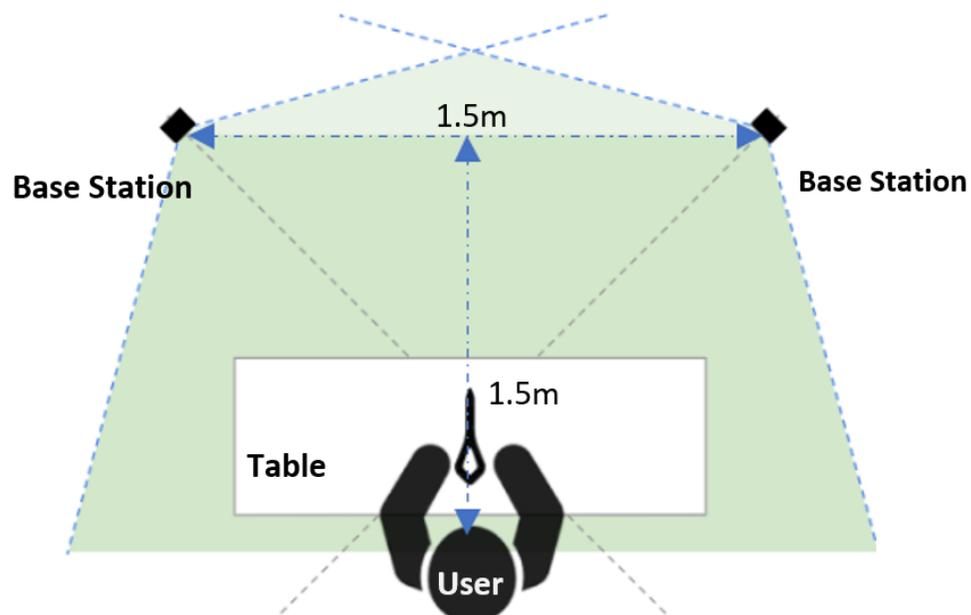


Figure 23: Base station positions to achieve optimized tracking for Logitech VR Ink.

The PC described above was pre-loaded with the experiment software and the instructions on how to set up. We delivered the PC and VR equipment to the participants that requested equipment drop-off. Participants that already owned HTC Vive Pro and the Logitech VR Ink received the software and the instruction sheet from us via online file sharing. Overall, the experiment took about one hour, with participants in VR for ~45 to 50 minutes and ~10-15 minutes setup.

Before starting the experiment, participants had to provide informed consent and then complete a demographic questionnaire. This was done via online forms. The main experiment was divided up into two interaction modes for the stylus, each with six blocks (one per SF). Each block consisted of eight sequences, one for each of the 8 IDs. In each sequence, participants were presented with 15 targets (i.e., trials). The participant had to successfully select at least 50% of the 15 targets to move on to the next sequence. To begin each sequence, they had to select the first target to begin the timer. The first selection in each sequence was thus not logged as it just started the sequence. This target was selected again as the last target in the sequence, ending the sequence.

After participants finished all the blocks for the two stylus interaction modes, the software would exit to desktop automatically after a few seconds. At this stage, the participants filled out the post-study questionnaire about their experience and their preferred interaction mode for the stylus. We compensated them a few days after the study was done with a \$20 (CAD) Amazon digital gift card. In the end, participants sent the data logged by the software back to the researcher via email.

5.5 Experiment Design

Our experiment employed a within-subjects design with three independent variables: Scale Factor, ID (index of difficulty) and Stylus Interaction Mode:

Scale Factor (SF): 1, 1.3, 1.6, 1.9, 2.2, 2.5.

ID: 1.5, 2, 2.3, 2.8, 3, 3.3, 3.7, 4.3.

Stylus Interaction Mode: No-Snap, Snap.

The ID values were generated from the following ten combinations of A and W (in pixels):

<i>ID</i>	1.5	2	2.3	2.8	3	3.3	3.7	4.32
<i>A</i>	150	450	200	900	750	950	990	1000
<i>W</i>	80	150	50	150	100	100	80	50

Table 5: Amplitude and Width pairs with their respective Index of Difficulty.

The SFs were applied to the 3D tracker stylus position in VR, as described in Chapter 3. IDs were calculated according to Equation 1, using the SF of 1 (i.e., 1-to-1 mapping). SF ordering was counterbalanced according to a balanced Latin squared. Within each SF, ID order was randomized, with one ID per sequence (i.e., circle) of 15 targets. Stylus interaction mode was counterbalanced by toggling the first encountered interaction mode between different participants (i.e., odd-numbered participants encountered the No-Snap interaction mode first).

Like our previous study, we used a set of pre-selected amplitude and width pairs, rather than fully crossing a selection of amplitude and widths. We again carefully chose our amplitude and width pairs so that they would cover a wide range of IDs.

Our dependent variables included:

- **Movement time:** the average selection time, in milliseconds.

- **Error rate:** the average proportion of targets missed (as a percent).
- **Throughput** (in bits per second, bps): calculated according to the *ISO 9241-9* standard and based on Equation 2 [27, 30, 51, 68, 74].
- **Target entry count:** number of times the cursor entered a target prior to selection. Higher target entries may indicate some control problems, with an ideal selection task having a target entry of 1 [53].

In total, participants each completed two interaction modes \times 6 SFs \times 8 IDs \times 15 trials (i.e., individual target selections) for 1440 selections in total, 720 for each interaction mode. Our analysis is thus based on 12 participants \times 1440 trials = 17280 selections in total and 8640 for each stylus interaction mode.

5.6 Results

Similar to our previous study, we used RM-ANOVA and where it failed to find a significant main effect for scale factor, we employed non-inferiority testing to instead test for statistical equivalence. Horizontal bars (•...•) indicate significant pairwise differences with Bonferroni adjustments between different scale factors.

5.6.1 Throughput

Assumption of sphericity was violated in case of throughput for scale factor, $\chi^2(14) = 25.58$, $p = .043$). We applied Greenhouse-Geisser corrections ($\epsilon = .53$). The assumption of sphericity was not violated in the case of stylus interaction mode and the interaction effect between stylus interaction mode and scale factor.

RM-ANOVA on throughput revealed a significant main effect for scale factor ($F_{2.68, 29.51} = 52.96$, $p < .001$, $\eta_p^2 = .82$, power = 1.00 ($\alpha = .05$)). There was also a significant

main effect in case of stylus interaction mode ($F_{1, 11} = 21.9, p = .001, \eta_p^2 = .66, \text{power} = .98 (\alpha = .05)$). The analysis however failed to find a significant interaction effect between scale factor and stylus interaction mode ($F_{5, 55} = 1.25, p = .29$). Figure 24 breaks down mean throughput scores across scale factors for stylus interaction modes. Our hypothesis failed in case of TP across different SF.

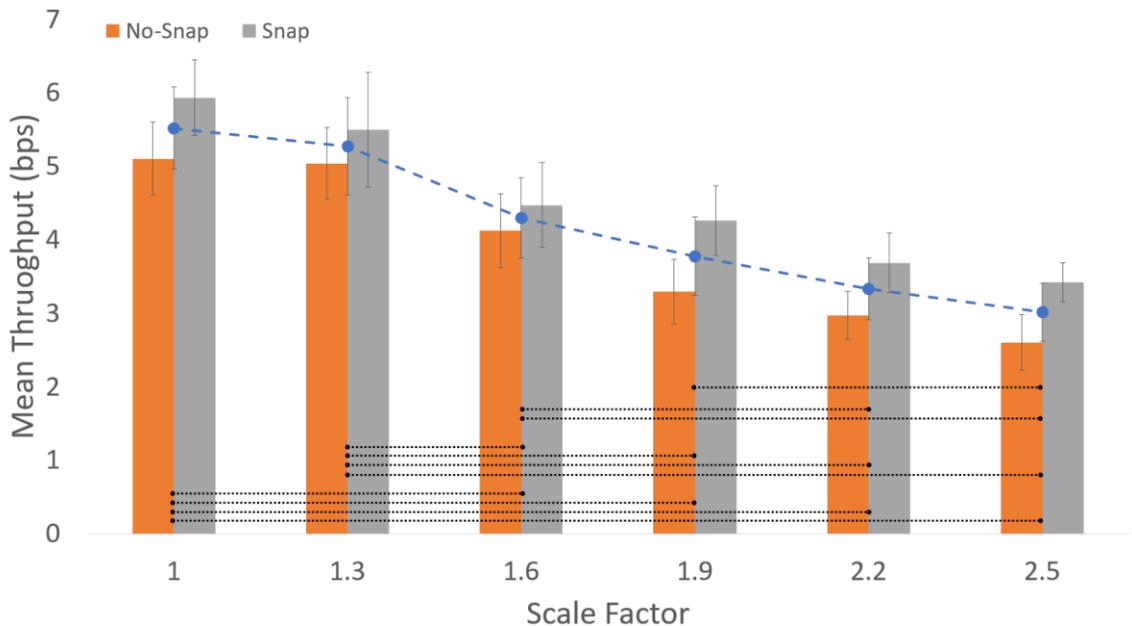


Figure 24: Mean TP (calculated based on ID_e) for each SF value and stylus interaction mode. Error bars indicate 95% CI.

We found these throughput scores to be higher than what we were expecting for a stylus in 3D. This fact is also evident if we compare our findings to other Fitts' law studies on stylus or pen input, usually below five close to 4.7 bps on average [60, 75]. We decided to include analysis on throughput calculated based on ID rather than ID_e (see Equation 2).

As depicted in Figure 25, throughput based on ID seems to be closer to past findings for stylus or pen input in VR [60, 75]. Assumption of sphericity was not violated in the

case of scale factor, stylus interaction mode and the interaction effect between stylus interaction mode and scale factor based on Mauchly's test.

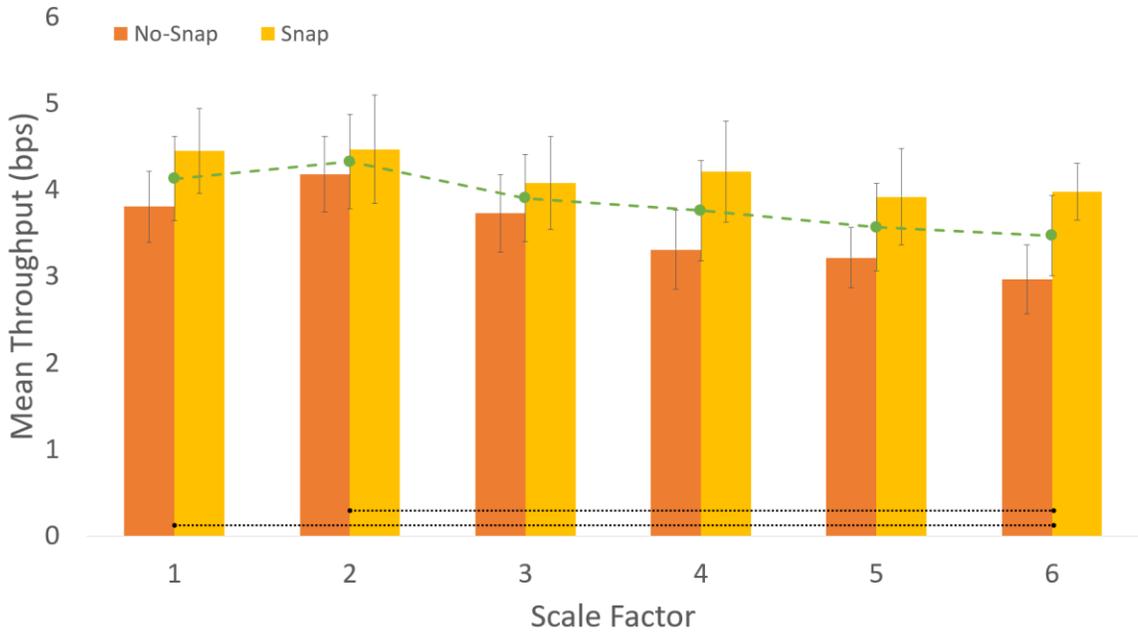


Figure 25: Mean TP (calculated based on ID) for each SF value and stylus interaction mode. Error bars indicate 95% CI

RM-ANOVA on throughput revealed a significant main effect for scale factor ($F_{5, 55} = 6.45, p < .001, \eta_p^2 = .37, \text{power} = .99 (\alpha = .05)$). There was also a significant main effect in case of stylus interaction mode ($F_{1, 11} = 16.87, p = .002, \eta_p^2 = .6, \text{power} = .96 (\alpha = .05)$). The analysis however failed to find a significant interaction effect between scale factor and stylus interaction mode ($F_{5, 55} = 1.8, p = .12$).

5.6.2 Error Rate

Assumption of sphericity was violated in case of scale factor, $\chi^2(14) = 24.76, p = .043$. We applied Greenhouse-Geisser corrections ($\epsilon = .58$). We found no significant main effect in case of error rate for different SFs ($F_{2.92, 32.12} = 2.51, p = .07$).

We used non-inferiority testing with an in-difference zone of 6.66, see Table 6. Based on our findings error rate seems to be consistent across moderate SFs, which is in line with our hypothesis, meaning error rates were similar across different SFs.

SF Pairs	Mean Diff.	1-tailed 95% conf. Interval	SD Error	Non-inferiority Comparison
1-1.3	-0.821	< 3.477	1.072	3.477 < 6.66
1-1.6	-1.007	< 3.737	1.272	3.737 < 6.66
1-1.9	-2.674	< 1.621	1.152	1.621 < 6.66
1-2.2	-2.083	< 2.252	1.163	2.252 < 6.66
1-2.5	-3.056	< 0.544	0.965	0.544 < 6.66

Table 6: Mean error rate differences and non-inferiority test results.

Sphericity was not violated for stylus interaction mode and the interaction effect between stylus interaction mode and scale factor. Our analysis did not find significant main effects in the case of scale factor and the interaction effect between stylus interaction mode and scale factor. Figure 26 breaks down error rate scores for different SFs for each mode.

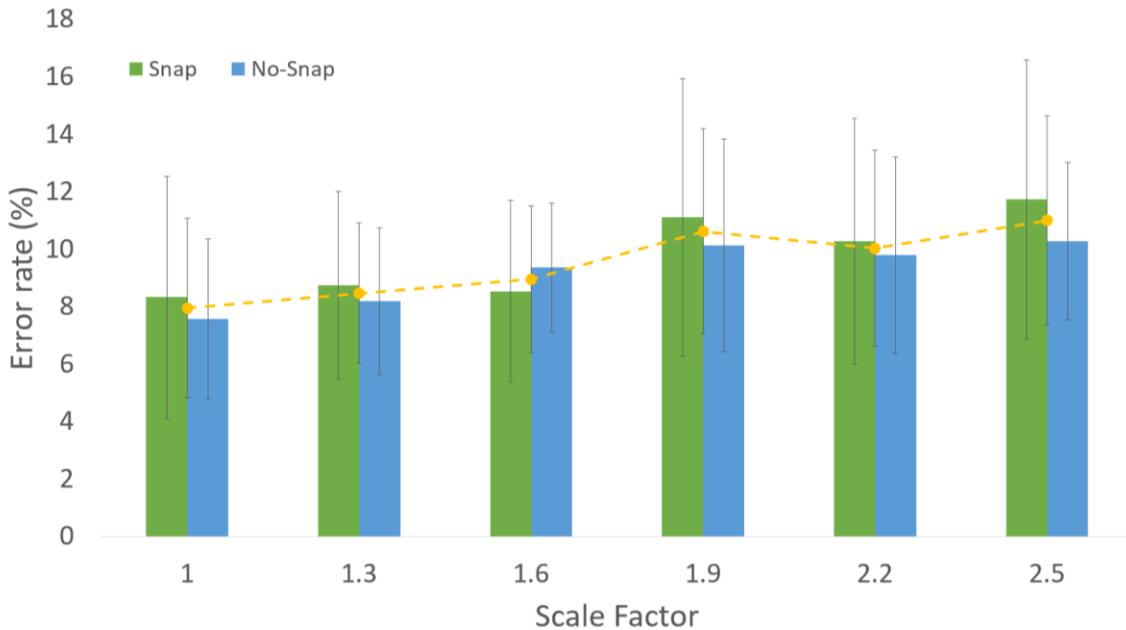


Figure 26: Mean error rate for each SF and stylus interaction mode. Error bars indicate 95% CI.

5.6.3 Movement Time

RM-ANOVA revealed a significant main effect in the case of movement time. The assumption of sphericity was not violated for SF, stylus interaction mode and interaction effect between the two based on Mauchly's test of sphericity.

There was a significant main effect of scale factor on MT ($F_{5, 55} = 4.17, p = .003, \eta_p^2 = .27, \text{power} = .93 (\alpha = .05)$) and stylus interaction mode ($F_{1, 11} = 10.60, p = .008, \eta_p^2 = .49, \text{power} = .84 (\alpha = .05)$). The analysis failed to find significant main differences for interaction effect between scale factor and stylus interaction mode ($F_{5, 55} = 1.79, p = .12$).

Results indicate that higher SF values resulted in a higher mean movement time, suggesting participants moved slower with higher SFs. No-Snap interaction mode had a higher mean MT compared to Snap for the stylus. Our hypothesis failed in the case of MT.

Figure 27 depicts our findings divided up for different interaction modes.

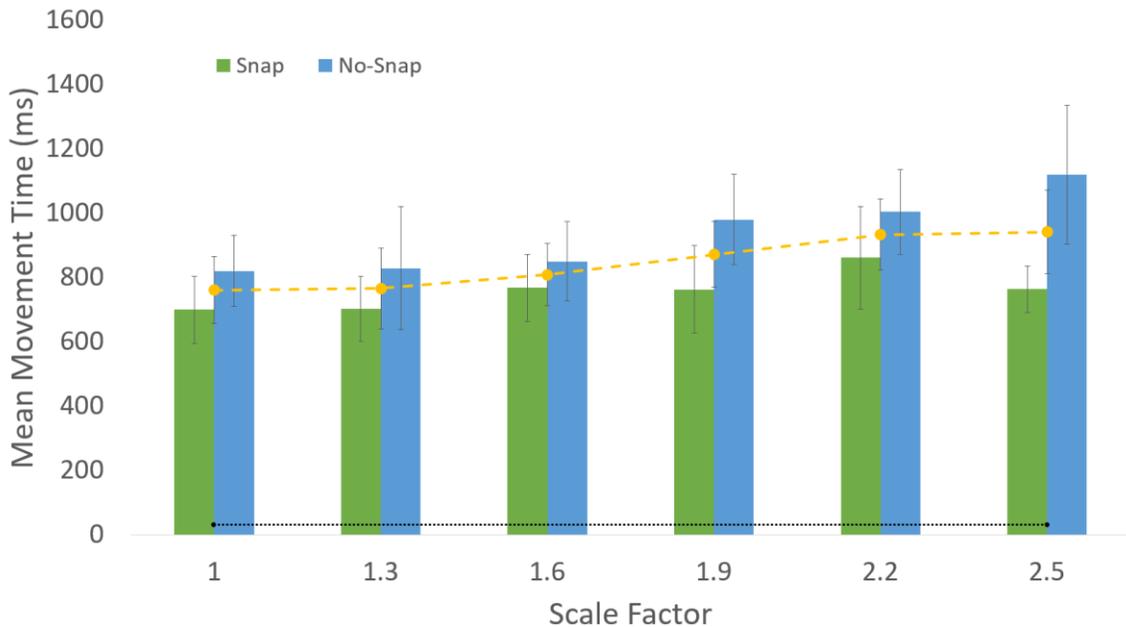


Figure 27: Mean MT for each SF value and stylus interaction mode. Error bars show 95% CI.

5.6.4 Target Entry Count

As seen in Figure 28, higher SFs yield slightly higher target entry counts, suggesting participants had more difficulty getting the cursor into the target before selection. The assumption of sphericity was not violated for scale factor, stylus interaction mode and interaction effect between the two, so results were analyzed without any corrections applied to degrees of freedom.

There was a significant main effect of SF on target entry count ($F_{5, 55} = 12.5, p < .001, \eta_p^2 = .53, \text{power} = 1.00 (\alpha = .05)$). Higher SF resulted in average higher target re-entries for correct selection. Our analysis failed to find a significant main effect in case of stylus interaction mode ($F_{1, 11} = 1.08, p = .32$) and the interaction effect between scale factor and stylus interaction mode ($F_{5, 55} = .27, ns$). Our hypothesis failed for the target entry count.

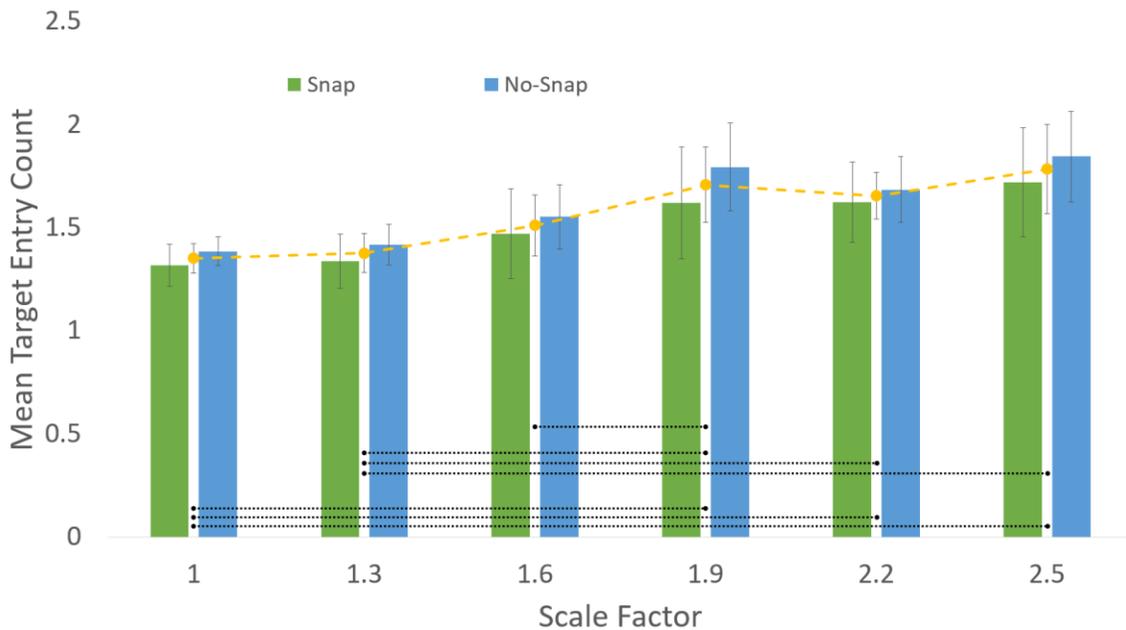


Figure 28: Mean target entry count for each SF and interaction mode. Error bars show 95% CI.

We analyzed if the target entry count was affected by the target size using for consistency with our previous study. The assumption of sphericity was violated for target width ($\chi^2(5) = 12.5, p = .029$) but not for stylus interaction mode and the interaction effect between the two, as indicated by Mauchly's test. We used Greenhouse-Geisser correction ($\epsilon = .69$) for target width. We found a significant main effect of target width on target entry count ($F_{2.07, 22.83} = 15.75, p < .001, \eta_p^2 = .58, \text{power} = 1.00 (\alpha = .05)$).

Figure 29 depicts the mean target entry count for different target widths. Our analysis found a significant interaction effect between stylus interaction mode and target width ($F_{3, 33} = 11.83, p < .001, \eta_p^2 = .51, \text{power} = .99 (\alpha = .05)$). This indicates that target size had different behaviour across the two different interaction modes in our study. Results suggest smaller targets were harder to hit upon initial entry and, on average, required more re-entries to select.

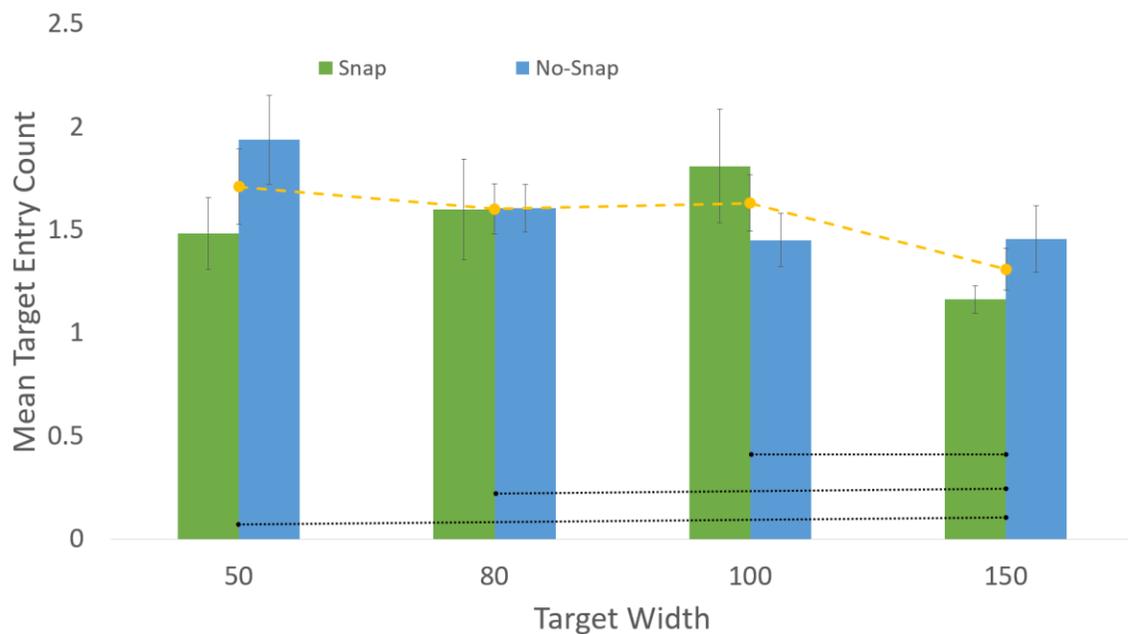


Figure 29: Mean target entry count for each target width and stylus interaction mode. Error bars show 95% CI.

5.6.5 Fitts' Law Analysis

We conducted Fitts' law analysis by performing a linear regression of MT onto ID. Figure 30 depicts the relationship between MT and the ID values we used in our experiment. We performed linear regression separately for two stylus interaction modes using conventional ID (i.e., the 8 IDs listed in Table 5). Fitts' law regression for Snap interaction mode yielded a better fitting model.

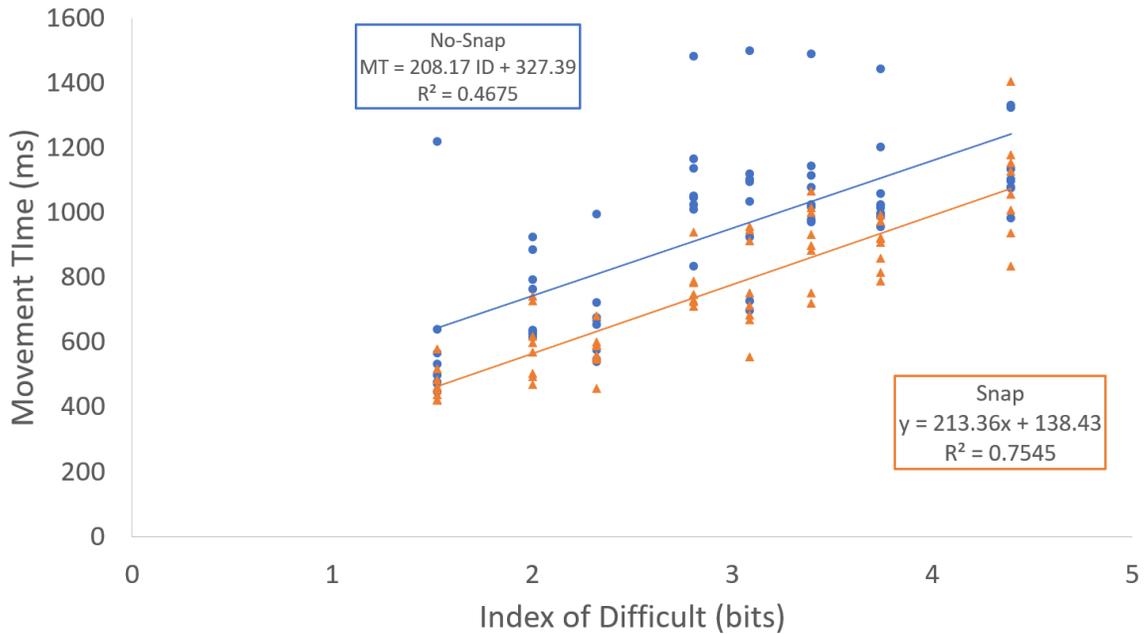


Figure 30: Linear regression of MT on ID for both stylus interaction modes.

5.6.6 Effective Width Analysis

We analyzed the effective width (W_e). Unlike our previous study, results indicate that participants were not making more accurate selections with higher SFs. Based on Figure 31, it seems effective width is slightly higher for the No-Snap stylus interaction method.

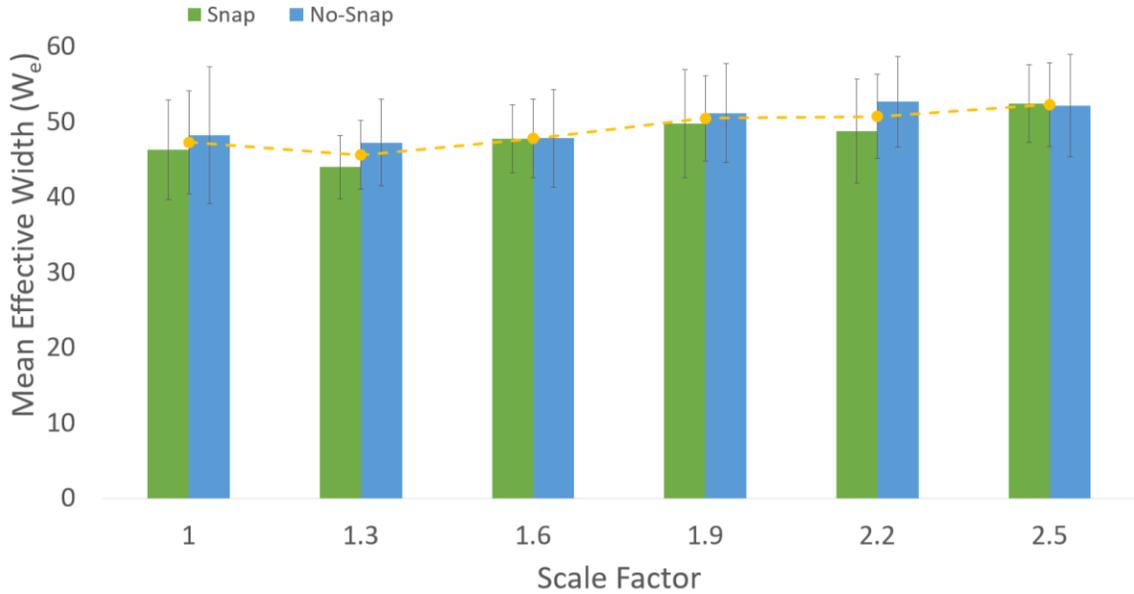


Figure 31: Mean W_e for different SFs and stylus modes in our experiment. Error bars show 95% CI.

5.6.7 Post-Questionnaire

We used the device assessment questionnaire provided by *ISO 9241-9* [27] to evaluate fatigue, accuracy and the overall experience of using table and stylus input method with WVS. Participants had to rate each phrase from 1 (*lowest*) to 5 (*highest*). See Figure 32. We did not compare results across different SFs since participants were unlikely to notice differences in the SFs and different stylus interaction modes. 83.3% of participants reported preferring Snap interaction mode and 8.3% reported liking both. Only one participant reported preferring No-Snap interaction mode for the stylus.

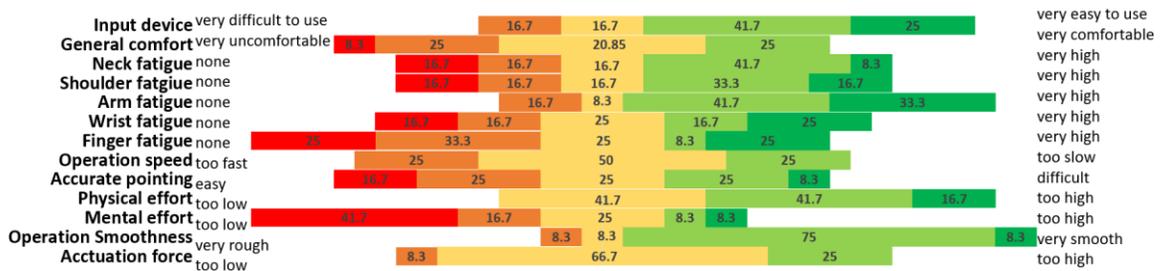


Figure 32: Device Assessment Questionnaire. Label numbers indicate the percentage of participants choosing each answer.

5.7 Discussion

Overall, participants found WVS without a physical panel easy to use, smooth to operate and to require low mental but high physical effort to use as evident by Figure 32. There also seems to be some levels of neck, shoulder, arm and wrist fatigue, which is not uncommon for Fitts' law studies and in-air VR interactions. Most of our participants reported preferring the Snap interaction mode for the stylus.

Our analysis found significant main effects for scale factor on throughput in contrast to our previous study. Throughput seems to decrease with higher scale factors. We also found a significant main effect in the case of SF on movement time and target entry count. We performed non-inferiority testing only in case of error rate. Results indicated that WVS without tactile panels and 3D stylus tracking is no worse than 1-to-1 mapping in case of error rate. However, as evident in Figure 26, error rate scores seem to be on an increasing trend with higher scale factors.

5.7.1 General Discussion

Overall, our analysis found that throughput scores decreased with higher SF values (see Figure 24) and we found higher error rates (see Figure 10 and Figure 26) compared to our previous study. Worse performance scores were expected since participants were selecting in-air targets with 3D tracking compared to our first experiment [75]. In the case of movement time, however, our results indicate lower movement times for our second study (see Figure 11 and Figure 27). This is not surprising since we employed 3D tracking for our second experiment.

We did not run non-inferiority testing in case of throughput since our analysis revealed a main effect for scale factor. Based on Figure 31, effective width did not behave

the same as our previous experiment (see Figure 15), i.e., effective width did not decrease with higher scale factors once we removed the haptic feedback and employed 3D stylus tracking. This could explain why throughput was not consistent across different scale factors in our second study. Another explanation for our results with TP could be that we did not use the same scale factors as in our first experiment. Another explanation for the main effect of scale factor on throughput could be the lack of haptic or tactile feedback in our second study compared to our first one. Furthermore, we only scaled the motion of the user and not the virtual panel size in VR compared to our previous study, which could also contribute to our findings for throughput. We note that we also used a smaller *width* and *height* in Equation 4 (i.e. a smaller real rectangular panel area) compared to our first study, which could also contribute to this.

Higher scale factors resulted in higher target entry counts similar to our first study (see Figure 12). Similarly, smaller targets had higher target entry counts, as seen in Figure 29. Overall, across different scale factors, Snap had lower target entry counts and MT and a higher TP compared to No-Snap. This behaviour was not unexpected as we expected snapping to help with selecting targets. As for target size, our analysis found an interaction effect between scale factor and stylus interaction mode. Except for the target width of 100, Snap appears to have lower target entry counts across different target sizes. We suspect an undetected bug in our software might have caused this.

5.7.2 Limitations

We were limited in the number of participants we could recruit due to the COVID-19 global pandemic. Although we provided instructions on setting up the VR tracking space, small differences in how participants did the setup could still have some effect on the results.

Also, adding more participants and the data or even changing the analysis method could potentially yield different results. More studies are required to determine the best choice for in-difference zones in Fitts' law studies.

Additionally, we would like to note that the Logitech VR Ink we used has known issues and limitations in 3D tracking and was not the final version of the product. We also note that we did not compare our qualitative results (i.e. device assessment questionnaire results) to our previous study. Furthermore, we did not compare across different stylus interaction modes since we were mostly interested in the effects of scale factors over stylus interaction mode. However, we believe our findings can still be useful and can help provide some insight into perceptual illusions for VR researchers and designers.

5.8 Conclusion

In this study, we employed Warped Virtual Surfaces without tactile physical panels and with 3D tracking for in-air selections on virtual panels in HMD-VR. We evaluated the effects of surface warping on task performance in terms of movement time, throughput, error rate and target entry count across different scale factors and with two different stylus interaction modes, Snap and No-Snap (See 5.5).

Our results indicate that without tactile physical panels or tablets, WVS affects throughput negatively with higher scale factors. However, in terms of error rate performance, WVS without tactile physical panels performed consistently across different scale factors. However, we found higher error rates compared to our first study. Results for MT compared to results from our first experiment, which did not employ 3D stylus tracking, showed that WVS with 3D tracking had lower MT in 1-to-1 mapping even without a tactile physical panel. We also found higher target entry counts compared to our

first experiment. Overall, Snap performed better compared to No-Snap and was the preferred stylus interaction mode among participants.

Chapter 6: Conclusions

Based on our findings, we conclude that Warped Virtual Surfaces is a viable complementary VR interaction technique to other techniques that include panels or tablets. We showed that with a physical panel or tablet, WVS had little impact on selection performance. In fact, with non-inferiority testing, we showed that performance under SFs was no worse than 1-to-1 mapping in terms of throughput and error rate. For in-air interactions (i.e. without a tactile physical panel or tablet) and using a smaller real panel area, WVS had a negative impact on performance in terms of throughput with higher SFs. However, we found performance in terms of error rate to be no worse than 1-to-1 mapping (i.e. no warping). We found a decreasing trend in throughput scores and an increasing trend in movement time for higher SF values in both studies.

Overall, participants performed worse without a tactile physical panel or tablet (i.e. in-air interactions). We suspect the lack of haptic feedback and the smaller real panel area caused this negative impact on selection performance. However, further studies and experiments are required to fully understand the impact of smaller panels. We also note that in our first study, participants used the tablet while it was positioned on a table. In contrast, participants were holding the virtual panel with the Vive controller in our second study. This could also contribute to our different findings between our two studies and requires further studies to understand the effects entirely. We also used 3D tracking and did not change the size of the virtual panel in our second experiment, which could also contribute to our different findings across the two studies.

We recommend 3D tracking whenever possible since it appears to decrease movement time even without a tactile physical panel present (See Figure 11 and Figure

27). We recommend using modest scale factors (i.e. no higher than 1.6). Based on our findings, there appears to be a shift in performance scores for SFs higher than 1.6. (See Figure 28, Figure 27 and Figure 26). We also recommend snapping in the absence of a tactile or physical panel. Our results indicate that overall, participants had worse performance scores with No-Snap stylus interaction mode. We believe snapping helped users with depth perception in VR. Snapping was also reported to be the preferred stylus interaction mode among the majority of our participants. We also suggest using bigger target widths whenever possible. Our analysis indicated that participants had higher target entry count rates for smaller targets, meaning they had some difficulty selecting smaller targets (See Figure 13 and Figure 29).

Higher scale factors seem to impact throughput negatively in the absence of a physical tactile panel or a tablet, as evident by our analysis (Figure 24 and Figure 25). However, with a tactile panel or tablet, higher SFs seem to have little or much less negative impact on throughput scores, as evident from Figure 9 and our non-inferiority test results. We do not recommend very high SF values. Using high scale factors would increase the movement speed of the virtual stylus to uncontrollable levels. High SFs would translate a minimal physical movement into a much bigger virtual movement. This breaks the VR experience for the user, makes the technique unusable and the stylus uncontrollable. Our target entry count analysis across different scale factors reinforces this notion (See Figure 12 and Figure 28). Our movement time analysis also supports this claim, as evident from Figure 11 and Figure 27, average movement time seems to be increasing for higher SFs.

6.1 WVS Applications

WVS can be used for artists and designer that are interested in immersive workflows or VR design sessions. Our approach uses cheap and affordable hardware. WVS enables users with a fix-sized physical panel or drawing tablet to get a bigger virtual panel without extra hardware and performance cost. It also has applications for 3D in-air drawing programs in VR like Tilt Brush¹³ or Gravity Sketch¹⁴. WVS could also be employed for writing in VR, for example, in education contexts, albeit some modification might be required on where to choose the warping origin for different scenarios. We believe WVS could be an alternative to classic UI items such as scrollbars or drop-down menus for 3DUIs, by expanding the virtual panel space when there are more items to show to the user.

WVS could be useful with small, lightweight arm-mounted touchscreens to facilitate tactile interaction with 3D menus or similar applications to PIP and WIM [70, 71]. WVS can complement other tablet and stylus-based interaction techniques for VR, such as the HARP system [50], the Virtual Notepad [61]. Interaction techniques like snappable panels or surfaces could employ WVS in various scenarios. WVS could potentially help with fatigue, but further studies are needed to determine to what extent.

Other haptic devices with limited interaction space, like the Phantom, could potentially also benefit from WVS by expanding their virtual reach. Warping techniques like WVS could be beneficial when we have a limited physical tracking space. Similar to RDW [64] and haptic retargeting [6], WVS overcomes the limits of the tracking space.

¹³ <https://www.tiltbrush.com/>

¹⁴ <https://www.gravitysketch.com/>

6.2 Points on Conducting Remote Experiments

We faced numerous new challenges in conducting our study during the COVID-19 pandemic and doing the study remotely potentially introduced confounding variables to our study. In this subsection, we summarize our experience running studies remotely during the COVID-19 global pandemic.

We ended up reducing the number of trials participants had to go through for our second study compared to what we originally intended. The main contributor to this decision was the fact that we had to consider the time it took each remote participant to set up the equipment and VR tracking area, as well as the time it took to complete a session of our experiment. We also got very few comments and engagement from our participants compared to our experience running in-person studies.

We also had to consider safety (e.g., participants bumping into things while in VR), hardware equipment disinfection protocols and setup consistency between participants. If our experiment required a large movement space, physical safety could have become an issue. We mitigated participants bumping into objects by asking participants to sit behind a table with some space for hand and arm movement. For COVID-19 safety, we disinfected our equipment before and after drop-off and also waited a few days before getting the equipment to the next participant. We minimized contact between participants and us by providing an instruction sheet on how to use the software and complete a session of the study. This instruction sheet also helped with consistency in setup between participants.

In general, doing the study fully remote, compared to equipment drop-off took less preparation time and effort on our end. One major factor that made remote studies possible in our case was that we were not using custom-made hardware or prototypes. Also, VR

hardware nowadays is widely available. However, we did face some difficulties finding participants with the specific VR hardware requirements we needed for our second study. While HTC Vive Pro head-mounted displays are becoming increasingly common, especially among VR researchers and enthusiasts, the Logitech VR Ink is still a new product that relatively few people have.

On the other hand, our prototype software had to run smoothly and with effectively no intervention from the experimenter. We ended up spending extra development resources to make sure the experience was smooth throughout the experiment or that the software did not confuse first-time VR users or crash suddenly. Gathering the data and getting it back from participants was also a new challenge. However, this was one of the easier problems to solve thanks to the Internet and our relatively simple experiment design. This could become a problem if other data gathering methods are required; for instance, remote observations while participants are in VR, which will become extra challenging if participants need to move physically while in VR during the study.

6.3 Thesis Conclusion

Our participants liked the idea of warped virtual surfaces. Participants enjoyed using a bigger panel in VR with a smaller physical or real panel. Based on our findings, we recommend using modest SFs (i.e. no more than 1.6). We recommend snapping on virtual panels in VR when tactile physical panels are not an option or are challenging to use. We also recommend using big target sizes. We conclude that our technique shows promise as a method to extend physical surfaces in VR virtually. Further studies are required to determine in which situations it indeed does not influence user performance or experience,

as our results were somewhat mixed in this regard. Overall, we found movement time to increase and throughput to decrease with higher scale factors.

Results of our first study, which did not employ 3D tracking and tactile physical panels, suggest minimal performance impact of WVS. Throughput was flat across all SFs. Despite small differences in MT, it seems users made up their performance via a slight accuracy improvement, yielding constant throughput. Our second study, however, did not end up having the same results as our first study, more specifically in the case of throughput. We suspect the lack of a tactile physical panel and haptic feedback contributed to throughput inconsistencies across different scale factors. Generally, we found snapping to help with selection in the absence of physical panels.

6.4 Future Work

For future work, we would like to focus on smaller tactile physical panels and other prototypes like smartwatches that employ WVS. We also would like to design an experiment closer to real-world applications rather than pure Fitts' law experiments. We are also interested in exploring higher scale factors. It would also be noteworthy to determine the detection thresholds for WVS and to see how far we can push the illusion and surface warping without users realizing there is any warping or discrepancy in their movement in VR. Furthermore, we would like to see how WVS would behave when complementing other tablet or panel-based VR techniques such as WIM and PIP or as an alternative to drop-down menus and lists for 3DUIs.

Appendices

Appendix A

A.1 Consent Form for Experiment 1

CUREB clearance #:106142_____



Consent Form

Title: Towards "Walk-Up" Usable 3D User Interfaces

Funding Source: NSERC

Date of ethics clearance: October 09, 2019

Ethics Clearance for the Collection of Data Expires: August 31, 2020.

Researchers: Amir Didehkhorsid, Carleton School of Information Technology

This study involves one 60 minute experiment. The experiment involves wearing a head-mounted display (e.g., HTC Vive) while performing tasks in a virtual environment such as selecting objects in the environment using the tracked tablet and stylus. Software will automatically and anonymously log your task performance data during participation.

Like most virtual reality systems, ours uses a stereo 3D display. Hence you must have normal or corrected-to-normal stereo viewing capabilities to participate – if you can see the 3D effect in 3D movies, you should be fine. There is thus also a minor risk of eye fatigue, headache, or nausea, consistent with the use of stereo displays (e.g., 3D movies) for about 10% of the population. Should you experience such symptoms, you are encouraged to take a break to alleviate the discomfort, or alternatively to withdraw from the study.

You have the right to end your participation in the study at any time, for any reason, up until completion of the experiment. If you withdraw from the study, all information you have provided will be immediately destroyed.

As a token of appreciation, you will receive \$10 upon completion of the experiment. This is yours to keep, even if you withdraw from the study.

All research data, including audio/video recordings and any notes will be encrypted and stored on the researcher's password-protected hard drive. Any hard copies of data (including any handwritten notes or USB keys) will be kept in a locked cabinet at Carleton University. Research data will only be accessible by the researcher.

Once the project is completed, all research data will be kept in anonymous form indefinitely, and potentially used for other research projects on this same topic. If

Page 1 of 2

This document has been printed on both sides of a single sheet of paper.
Please retain a copy of this document for your records.

you would like a copy of the finished research project, you are invited to contact the researcher to request an electronic copy which will be provided to you.

The ethics protocol for this project was reviewed by the Carleton University Research Ethics Board, which provided clearance to carry out the research. Should you have questions or concerns related to your involvement in this research, please contact:

CUREB contact information:

Professor Shelley Brown, Chair (CUREB-B)
Professor Andy Adler, Vice-Chair
Carleton University Research Ethics Board
Carleton University
511 Tory
1125 Colonel By Drive
Ottawa, ON K1S 5B6
Tel: 613-520-2517
ethics@carleton.ca

Researcher contact information:

Seyed Amir Didehkhorsid
School of Information Technology
Carleton University
Email: Amir.Didehkhorsid@carleton.ca

Supervisor contact information:

Rob Teather
School of Information Technology
Carleton University
Tel: 613-520-2600 ext. 4176
Email: Rob.Teather@carleton.ca

I _____, choose to participate in a study on 3D user interfaces.

Signature of participant

Date

Signature of researcher

Date

A.2 Consent Form for Experiment 2-Dropoff

Informed Consent Form

▲ Name and Contact Information of Researchers:

Seyed Amir Didehkhorshid

Email: *Amir.Didehkhorshid@carleton.ca*

Supervisor and Contact Information: *Dr. Robert Teather at Rob.Teather@carleton.ca*

Project Title

Selection performance using 3D interaction techniques with a 3D tracked Stylus

Project Sponsor and Funder (if any)

Carleton University Project Clearance

Clearance #: 113156 Date of Clearance: July 14, 2020

Invitation

You are invited to take part in a research experiment because you expressed your interest in participation. The information in this form is intended to help you understand what we are asking of you so that you can decide whether you agree to participate in this study.

To participate in this study, you must have normal or corrected to normal stereo vision (if you can see 3D effects in movies you have normal stereo vision) and be comfortable using a PC with an internet connection. You must not have COVID-19 or its symptoms such as dry cough and fever or be in self-isolation.

Your participation in this study is voluntary, and a decision not to participate will not be used against you in any way. As you read this form and decide whether to participate, please ask all the questions you might have, take whatever time you need, and consult with others as you wish.

What is the purpose of the study?

We are assessing the *usability and performance of a 3D tracked stylus interface* in VR. The data will be a great help for designers and developers of VR systems, and the VR/HCI research communities.

What will I be asked to do?

If you agree to take part in the study, we will ask you to:

1. Setup the VR equipment in case of equipment drop-off.
2. Answer a demographic questionnaire.
3. Complete a series of ISO standardized selection and pointing tasks (Fitts' Law).
 - You will be shown a series of targets and you will be tasked with selecting each target as accurately as possible.
4. Answer usability and device assessment questionnaires.

5. Send the data logged by the software back to the researcher via email.

Risks and Inconveniences

The risks level involved in this experiment are minimal. Using a VR head-mounted display for a brief time (~45 minutes) has an inherent small risk of cybersickness (e.g., nausea), but this is largely mitigated by the fact that you are seated stationary in this experiment (cybersickness typically presents when moving) and the current modern VR technology. Similarly, common VR-related risks (e.g., bumping into furniture) are also mitigated by you being seated.

All equipment is carefully disinfected before each participant in case of equipment drop-off.

Possible Benefits

You may not receive any direct benefit from your participation in this study. However, your participation may allow researchers to better understand and measure user performance in using 3D User Interfaces in VR with a stylus input modality.

Compensation/Incentives

You will receive a 20\$ Amazon digital gift card. You will get a digital code sent to the same email address you used to initially contact the researcher within 2-3 days after the study is completed.

No waiver of your rights

By signing this form, you are not waiving any rights or releasing the researchers from any liability.

Withdrawing from the study

If you withdraw your consent during the course of the study, all information collected from you before your withdrawal will be discarded or, unless you request that it be removed from the study data.

Once the experiment is complete you cannot withdraw, as your study data is provided anonymously and there is no way to link it back to your identity.

Confidentiality

The VR software will not be logging any identifying information in the study data. Other than on the consent forms, your name and information will not be stored. The online forms use a secure connection and will not store any personal information such as your IP or email address.

In case of equipment drop-off your address and contact information will be kept confidential and they will not be stored permanently and will be destroyed upon returning the equipment and the consent form.

Online video calls for questions and assistance with the setup and the experiment will be conducted via Zoom or Skype. The video calls will not be recorded and are held on decentralized servers.

We will treat your personal information as confidential, although absolute privacy cannot be guaranteed. No information that discloses your identity will be released or published without your specific consent. Research records may be accessed by the Carleton University Research Ethics Board in order to ensure continuing ethics compliance.

The results of this study may be published or presented at an academic conference or meeting, but the data will be presented so that it will not be possible to identify any participants unless you give your express consent.

You will be assigned a participant ID so that your identity will not be directly associated with the study data you have provided. All data, including coded information, will be kept in a password-protected a secure computer.

In case you will be granted course credit for taking part in the study, identifying information will be retained using a code until the course credit is granted.

Data Retention

After the study is completed, your de-identified data will be retained for future research use for up to 3 years.

In case of equipment drop-off, contact information and address will be destroyed upon returning the VR hardware equipment.

New information during the study

In the event that any changes could affect your decision to continue participating in this study, you will be promptly informed.

Ethics review

This project was reviewed and cleared by the Carleton University Research Ethics Board B. If you have any ethical concerns with the study, please contact Carleton University Research Ethics Board (by phone at 613-520-2600 ext. 4085 for CUREB B or by email at ethics@carleton.ca.)

Statement of consent – print and sign name

I voluntarily agree to participate in this study. Yes No

Signature of participant

Date

Research team member who interacted with the participant

I have explained the study to the participant and answered any and all of their questions. The participant appeared to understand and agree. I provided a copy of the consent form to the participant for their reference.

Signature of researcher

Date

A.3 Consent Form for Experiment 2-Remote

Consent Form

Project Title: Selection performance using 3D interaction techniques with a 3D tracked Stylus

Clearance #: 113156

Date of Clearance: July 14, 2020

* Required

Name and Contact Information of Researchers:

Seyed Amir Didehkorshid

Email: amir.didehkorshid@carleton.ca

Supervisor:

Dr. Robert Teather

Email: Rob.Teather@carleton.ca

Invitation

You are invited to take part in a research experiment because you expressed your interest in participation. The information in this form is intended to help you understand what we are asking of you so that you can decide whether you agree to participate in this study.

To participate in this study, you must have normal or corrected to normal stereo vision (if you can see 3D effects in movies you have normal stereo vision) and be comfortable using a PC with an internet connection. You must not have COVID-19 or its symptoms such as dry cough and fever or be in self-isolation.

Your participation in this study is voluntary, and a decision not to participate will not be used against you in any way. As you read this form and decide whether to participate, please ask all the questions you might have, take whatever time you need, and consult with others as you wish.

What is the purpose of the study?

We are assessing the usability and performance of a 3D tracked stylus interface in VR. The data will be a great help for designers and developers of VR systems, and the VR/HCI research communities.

What will I be asked to do?

If you agree to take part in the study, we will ask you to:

1. Setup the VR equipment in case of equipment drop-off.
2. Answer a demographic questionnaire.
3. Complete a series of ISO standardized selection and pointing tasks (Fitts' Law).
 - o You will be shown a series of targets and you will be tasked with selecting each target as accurately as possible.
4. Answer usability and device assessment questionnaires.
5. Send the data logged by the software back to the researcher via email.

Risks and Inconveniences

The risks level involved with this experiment are minimal. Using a VR head-mounted display for a brief time (~45 minutes), has an inherent small risk of cybersickness (e.g., nausea), but this is largely mitigated by the fact that you are seated stationary in this experiment (cybersickness typically presents when moving) and the current modern VR technology. Similarly, common VR-related risks (e.g., bumping into furniture) are also mitigated by you being seated.

All equipment is carefully disinfected before each participant in case of equipment drop-off.

Possible Benefits

You may not receive any direct benefit from your participation in this study. However, your participation may allow researchers to better understand and measure user performance in using 3D User Interfaces in VR with a stylus input modality.

Compensation/Incentives

You will receive a 20\$ Amazon digital gift card. You will get a digital code sent to the same email address you used to initially contact the researcher within 2-3 days after the study is completed.

No waiver of your rights

By signing this form, you are not waiving any rights or releasing the researchers from any liability.

Withdrawing from the study

If you withdraw your consent during the course of the study, all information collected from you before your withdrawal will be discarded or, unless you request that it be removed from the study data.

Once the experiment is complete you cannot withdraw, as your study data is provided anonymously and there is no way to link it back to your identity.

Confidentiality

The VR software will not be logging any identifying information in the study data. Other than on the consent forms, your name and information will not be stored. The online forms use a secure connection and will not store any personal information such as your IP or email address.

In case of equipment drop-off your address and contact information will be kept confidential and they will not be stored permanently and will be destroyed upon returning the equipment and the consent form. Online video calls for questions and assistance with the setup and the experiment will be conducted via Zoom or Skype. The video calls will not be recorded and are held on decentralized servers.

We will treat your personal information as confidential, although absolute privacy cannot be guaranteed. No information that discloses your identity will be released or published without your specific consent. Research records may be accessed by the Carleton University Research Ethics Board in order to ensure continuing ethics compliance.

The results of this study may be published or presented at an academic conference or meeting, but the data will be presented so that it will not be possible to identify any participants unless you give your express consent.

You will be assigned a participant ID so that your identity will not be directly associated with the study data you have provided. All data, including coded information, will be kept in a password-protected a secure computer.

In case you will be granted course credit for taking part in the study, identifying information will be retained using a code until the course credit is granted.

Data Retention

After the study is completed, your de-identified data will be retained for future research use for up to 3 years.

In case of equipment drop-off, contact information and address will be destroyed upon returning the VR hardware equipment.

New information during the study

In the event that any changes could affect your decision to continue participating in this study, you will be promptly informed.

Ethics review

This project was reviewed and cleared by the Carleton University Research Ethics Board B. If you have any ethical concerns with the study, please contact Carleton University Research Ethics Board (by phone at 613-520-2600 ext. 4085 for CUREB B or by email at ethics@carleton.ca.)

Enter your name: *

Your answer _____

Statement of consent *

I voluntarily agree to participate in this study.

A.4 Instruction Sheet

CUREB-B Clearance # 113156

Step 1 - Consent Form

Please carefully read the consent form found here:

<https://forms.gle/iz7TwpRjeDRbFu9a6>

Step 2 - pre-experiment questionnaire

Please fill out the demographics questionnaire found here:

<https://forms.gle/pKoXwgMXtHK5aK6YA>

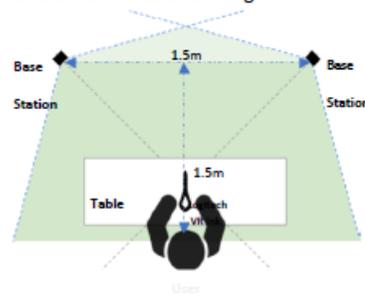
Step 3 – Equipment setup

Before we start the experiment, you will need to set up the base stations and the VR Head-Mounted Display (HMD).

Tracking Area Set up

Use the setup depicted below for the base stations:

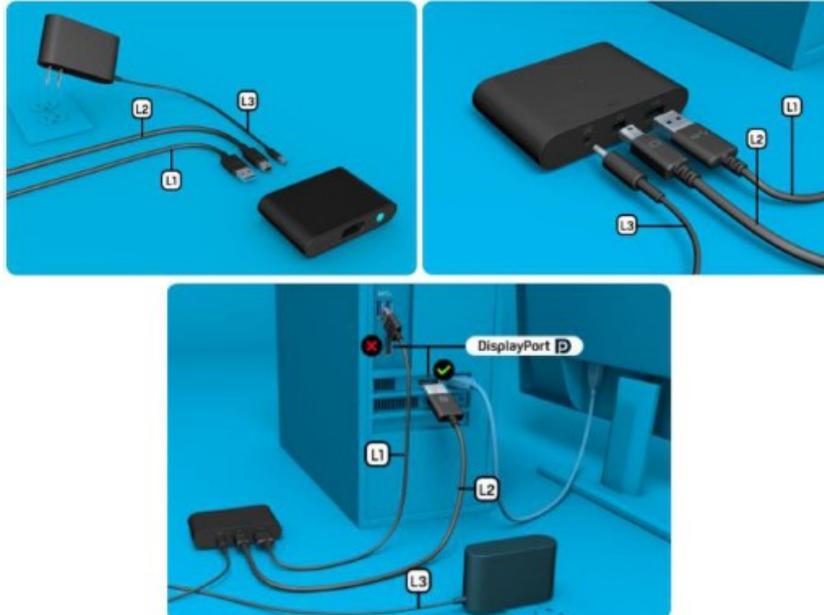
1. What you will need:
 - i. A chair.
 - ii. A table.
 - iii. A stand structure with 15-30cm height.



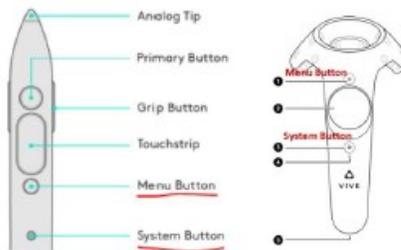
2. Place the base stations at 10 and 2 o'clock positions on the stands 1-1.5m apart.
3. Have them point towards the centre of where you will be sitting.
4. Sit at the centre, 1.5m away from the stations.
5. Always face towards the stations.

For the **best** tracking experience make sure the stylus can **always** be seen by **both** base stations.

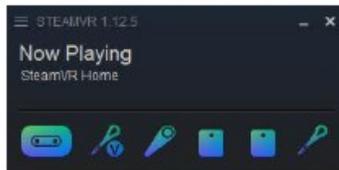
Equipment Set up



1. Find the link box and connect the cables as seen the images above.
 - If you need more help follow the guide found in the link below:
<https://www.vive.com/eu/setup/vive-pro-hmd/>
 2. Turn on the Logitech VR Ink and Vive Controller by holding down the System Button.
- If the status LED does not turn green upon turning on the devices, you must connect them to the PC:
 - In the SteamVR status window, right click on (any) controller icon and select **Pair Controller**.
 - Click on the button "I want to pair a different type of controller ..."
 - Press (and hold) both the **MENU** and **SYSTEM** buttons on Logitech VR Ink for a few seconds until the status LED on the stylus starts blinking blue.
 - Press (and hold) both the **MENU** and **SYSTEM** buttons on the Vive Controller a few seconds until the status LED on the stylus starts blinking blue

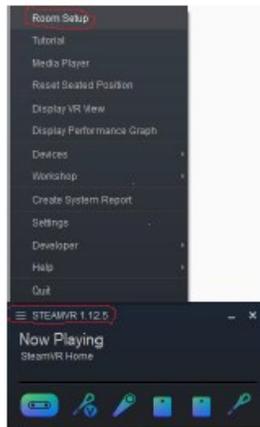


2. If everything is connected successfully SteamVR should look like this:



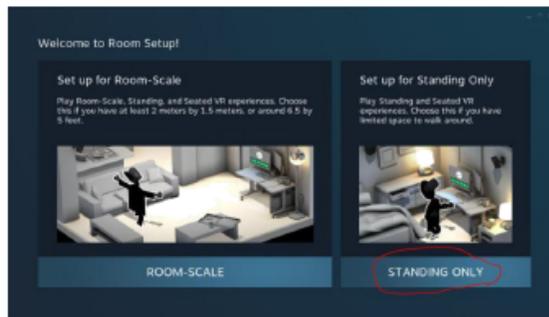
3. Next, do a room setup to configure the tracking space.

1. Click on the STEAMVR label to bring up the settings menu and then select Room Setup.



2. Select Standing Only and follow the on-screen steps to setup the tracking space.

3. During the setup, set the direction of the tracking space toward the base stations.



Step 4 – The Experiment

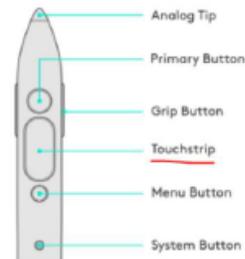
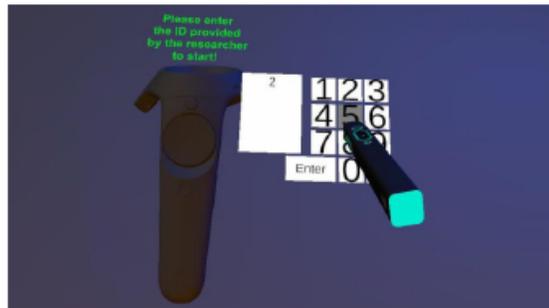
1. Next you need to open the Experiment Folder on the Desktop.
 - a. Once you open the folder, double click on WWS Experiment to run the application.

Folder	2020-06-10 2:05 PM	File folder	
Folder	2020-06-10 2:23 PM	File folder	
File	2020-06-09 7:05 AM	JSON File	3 KB
File	2020-06-10 2:23 PM	JSON File	10 KB
File	2020-06-10 2:23 PM	JSON File	7 KB
File	2020-06-10 2:23 PM	JSON File	7 KB
File	2020-06-10 2:23 PM	JSON File	10 KB
File	2020-06-05 12:34 PM	Application	1,060 KB
File	2020-06-05 12:34 PM	Application extension...	25,247 KB
File	2020-06-05 12:33 PM	Application	636 KB

2. Before you start the experiment please read and accept/sign the consent form.
3. Put on the HMD.
 - a. You can watch this video if you need assistance with wearing the HMD.
https://www.youtube.com/watch?v=EBUXPv76E3Q&feature=emb_logo
 - b. Make sure the headphones are covering your ears and that sound is enabled.



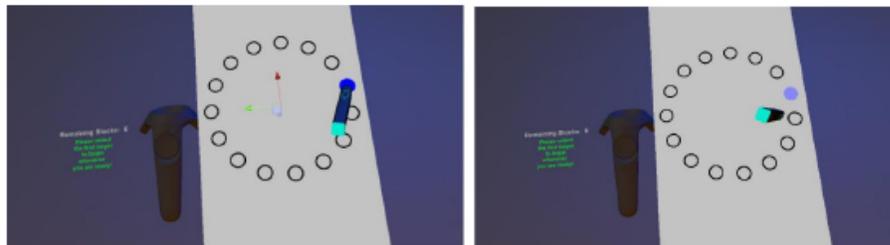
4. Pick up the stylus with your right hand, and the controller with your left hand.
5. After starting the application, you will be dropped in the virtual environment.
6. Please enter the ID number provided to you.
 - a. Select the numbers on the keypad by touching them with the stylus tip.
 - b. Upon hitting each one, they will change colour.
 - c. Use the **Touch Strip** button to select the targets.
 - i. Use **Enter** submit and finalize your ID.
 - ii. You could use **CE** to clear if you entered the wrong number.
 - iii. You cannot change your ID after you hit **Enter**.



Experiment Instructions

1. You will be presented with 15 targets, one of them will be highlighted for selection.
 - a. Select the targets by touching them with the stylus tip.
 - i. Targets change colour to indicate if the stylus tip is currently touching the target.
 - ii. Upon successfully selecting the target you will hear a "click" sound.
 - iii. You will hear a "beep" sound when a selection error occurs.
 - b. You can see how many Blocks are left.
 - c. You will repeat twice:
 - i. Once with Snapping mode.
 - ii. The other with Snapping disabled.
 - iii. Total of 12 blocks.

Please select the highlighted target as **accurately** as possible!



2. The application will log automatically.
 - a. You can take a break whenever you are at the start of a sequence. This is when you can see the text in green.
3. When done, targets will disappear and you will see a message saying you can remove the HMD.
4. The application will exit automatically after a few seconds of finishing the experiment.

Step 5 – Post Study Questionnaires

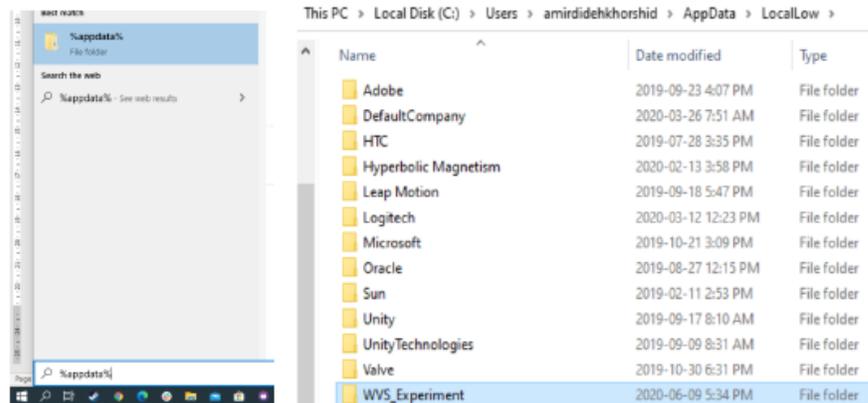
Please fill out the Device Assessment questionnaire found here:

<https://forms.gle/XDMezdRNfs9uh2Rt8>

Step 6 – Send the Data

After the software exits back to desktop, you will need to send the data to the researcher.

1. Click on the windows button and bring up the start menu
2. Type %appdata% and hit Enter on the keyboard. A window will open.
3. Go up a folder by using the shortcut key Alt + UP Arrow.
4. Double click on the LocalLow folder.
5. Look for the WVS_Experiment folder.
6. Put all the content in a zip file and email to the researcher at amir.didehkorshid@carleton.ca.
using the same email address you used to contact the researcher.



A.5 Demographics Questionnaire

Age *

Your answer _____

Gender

Female

Male

Non-Binary

Prefer not to share

Self-Identify

Other: _____

How often do you play VR? *

None at all

A little

A moderate amount

A lot

A great deal

How often do you play 3D first-person games? *

None at all

A little

A moderate amount

A lot

A great deal

A.6 Device Assessment Questionnaire

The force required for actuation was *

	1	2	3	4	5	
too low	<input type="radio"/>	too high				

Smoothness during operation was *

	1	2	3	4	5	
very rough	<input type="radio"/>	very smooth				

The mental effort required for operation was *

	1	2	3	4	5	
too low	<input type="radio"/>	too high				

The physical effort required for operation was *

	1	2	3	4	5	
too low	<input type="radio"/>	too high				

Accurate pointing was *

	1	2	3	4	5	
easy	<input type="radio"/>	difficult				

Operation speed was *

	1	2	3	4	5	
too fast	<input type="radio"/>	too slow				

Finger fatigue: *

	1	2	3	4	5	
none	<input type="radio"/>	very high				

Wrist fatigue: *

	1	2	3	4	5	
none	<input type="radio"/>	very high				

Arm fatigue: *

	1	2	3	4	5	
none	<input type="radio"/>	very high				

Shoulder fatigue: *

	1	2	3	4	5	
none	<input type="radio"/>	very high				

Neck fatigue: *

	1	2	3	4	5	
none	<input type="radio"/>	very high				

General comfort: *

	1	2	3	4	5	
very uncomfortable	<input type="radio"/>	very comfortable				

Overall, the input device was *

	1	2	3	4	5	
very difficult to use	<input type="radio"/>	very easy to use				

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