Selection Performance Using a Smartphone in VR with Redirected Input

by

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A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial fulfillment of the requirements for the degree of

Master of Science

in

Information Technology – Digital Media

Carleton University
Ottawa, Ontario

Abstract

We present a method to track a smartphone in VR using a fiducial marker displayed on the screen. Using WebRTC transmission protocol, we capture input on the smartphone touchscreen as well as the screen contents, copying them to a virtual representation in VR. We present two Fitts' law experiments assessing the performance of selecting targets displayed on the virtual smartphone screen using this method. The first compares direct vs. indirect input (i.e., virtual smartphone co-located with the physical smartphone, or not), and reveals there is no significant difference in performance due to input indirection. The second experiment assesses the influence of input scaling, i.e., decoupling the virtual cursor from the actual finger position on the smartphone screen so as to provide a larger virtual tactile surface. Results indicate a small effect for extreme scale factors. We discuss implications for the use of smartphones as input devices in VR.

Acknowledgments

I'm eternally thankful to my supervisor, Dr. Robert J. Teather for his constant support, guidance, trust, and understanding. This thesis, research, and even my education in Carleton would not have been possible without him. Robert shared his experience as a researcher and help with the funding of this study. I learned a lot from him and it opened the door to new opportunities, I will always be thankful and remember that.

I would also like to thank Dr. Audrey Girouard for a valuable lesson on how to correctly write scientific papers. My thanks to Dr. David Thue and Dr. Omair Shafiq for the experience in paper writing I gained in your courses. Thanks to my laboratory colleges for the fun and interesting environment in the workplace.

Thanks to all previous researchers, who work in this area which was an inspiration for me, to authors of the software projects, frameworks, and libraries I used in this research, to producers of VR hardware I used in studies and mentioned in this thesis.

Finally, I want to thank my mother, my brother, all my bigger family, and my friends for their belief in me and support. I would not be able to do this research without them cheering for me. I'm forever grateful for their trust and understanding.

Table of Contents

List of Tables

List of Illustrations

List of Appendices

Chapter 1: Introduction

Virtual reality (VR) presents a simulated environment through technical means, transmitted to a person through their senses: primarily vision, but also through hearing, touch, and sometimes others. Virtual reality systems usually simulate both exposure and reactions to the user; the user does not just see the environment, but the environment changes as a result of the user's actions, and conversely, the VR scene stimulates the user to act differently.

In recent years VR hardware has become more affordable. VR head-mounted displays (HMDs) have improved considerably and are now lighter and offer a larger field of view. This has led to the use of VR in many areas, such as education, art, and entertainment. For example, VR has been used in the study of human anatomy [58,81], chemistry [18,30], computer science [67], and even remote studying [65]. Artistic applications such as 3D modeling and painting in VR have also been widely employed [16,17,54], with new techniques prototyped to make it more efficient and comfortable [2]. Finally, the "killer app" for VR is still in the game industry. Studies about improved VR tracking [33,49] and interaction techniques [41,69] are done to make the VR gaming experience as immersive and comfortable as possible.

Software development tools for VR have improved as well. Today, popular and powerful game engines such as Unreal Engine[1] and Unity[2] fully support VR application development. They include support for the most popular VR HMDs, such as HTC Vive[3],

[1] https://www.unrealengine.com/
[2] https://unity.com/
[3] https://www.vive.com/

Oculus Rift[4], and Oculus Quest[5] as well as for the smartphone-based VR on Android and iOS-operated smartphones. All the most popular VR headsets (except smartphone-based) provide full 6 degrees-of-freedom (6DOF) pose tracking out of the box via special tracking devices – VR controllers, that provide several buttons and joysticks in addition to motion tracking capabilities. Yet, VR technology is still developing and has great potential, which allows us to research more innovative solutions in this area as well as possible integrations with other technologies.

Smartphones are another essential device developing quickly and are now ubiquitous. Smartphones have acquired many new capabilities in recent years, becoming full-fledged personal computers with high-resolution cameras and a great number of various sensors. Due to extreme popularity and increase in demand, smartphones have become cheaper and affordable to almost everybody. The history of smartphones and modern VR headsets are tied together. Among the first projects in smartphone-based head-mounted display (HMD) design started in 2011 in USC Institute for Creative Technologies by Olson et al. [62]. They devised the FOV2GO device[6], which was the first low-cost smartphone-based "cardboard" HMD prototype. Further evolution of the idea led to the creation of the first versions of modern VR headsets such as the Oculus Rift DK1 [12] and Google Cardboard[7]. The advent of low-cost, low-power LCD displays through the development of smartphones was directly applied in the development of modern LCD-based VR head-mounted displays.

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[4] https://www.oculus.com/rift-s/
[5] https://www.oculus.com/quest/
[6] https://www.markbolas.com/blank
[7] https://arvr.google.com/cardboard/

Smartphones now include gyroscopes that provide good rotational tracking and accelerometers, cameras, and GPS sensors that offer the potential for positional tracking. These features are utilized in much cheaper smartphone-based VR HMD options, such as Google Cardboard. However, this is just one example of VR-smartphone integration; smartphones offer potential not just as a display, but also as an interaction device in VR.

There are several studies examining the use of smartphones or wearable devices as VR input devices [3,13,87,34,39,47,48,51,53,71,80]. To date, none was able to track the smartphone's position and orientation with off-the-shelf VR headsets without attaching a bulky VR controller or tracking device to it. While affixing a VR controller to a smartphone provides good tracking, it requires an extra VR controller or sensor, which makes the smartphone less ergonomic. Thus, the smartphone becomes uncomfortable and awkward to use both in VR and out of the VR session until the controller is detached from the smartphone. While it is possible to track a smartphone with optical tracking systems like Vicon[8], such systems are very expensive and constrained to one room. These limitations make it impractical to track a smartphone in VR in such a fashion. Moreover, with the exception of recent work by Bai et al. [8], none of the previous solutions supported integrating the smartphone's capabilities in VR, as though it were normal smartphone usage.

Despite great progress in education and training, VR is still mostly used for gaming. And if players need to answer a phone call or chat message, they have to put off the VR headset, use the smartphone, and put the HMD back again, which reduces

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[8] https://www.vicon.com/

immersion and presence. Hence, it's the main reason why we need a smartphone in VR integration.

Meanwhile, the rich feature set provided by modern smartphones fits VR well. A smartphone's gyroscope can monitor the device's orientation with reasonable precision, which allows the smartphone to act like a 3DOF VR controller [47]. Smartphone touchscreens provide tactile feedback to the user, which is known to improve performance and presence [29]. The touchscreen can be used as a highly precise interaction surface for object manipulation and system control operations in VR. The previously mentioned features may be benefitted to provide default smartphone functionality to VR such as phone calls, messaging, photography, etc.

In this research, we propose a technique to support 6 degree-of-freedom (DOF) tracking of a smartphone in VR, without any additional sensors attached to the smartphone. Our method also presents a virtual replica of the smartphone in the virtual environment and copies the smartphone screen content to the virtual replica. This gives the user the ability to interact with the smartphone in VR in a fashion similar to how they would in reality.

Incorporating real objects into immersive VR, in general, requires addressing three challenges. First, one must implement 6 DOF tracking to detect the object pose. Second, one must somehow visualize the object in VR, including the object's possible visual changes in runtime. Third, one must provide a method to interact with the object in VR. In the case of smartphone-VR integration, we further specify the challenges:

1. Position and rotation tracking of the smartphone.
2. Smartphone screen translation and visualization in the HMD.

3. Efficient and comfortable smartphone usage in VR.

We briefly discuss each of these challenges. Note that although we have a technical solution to each challenge that we employ in our prototype (see Chapter 3), this research is primarily focused on the third challenge. To this end, we present a performance evaluation of our method.

1.1 Position and rotation tracking of the smartphone

Most currently popular VR HMDs use infrared light with special trackers to track the controllers and the display itself (e.g., as the user walks around a room) [4]. Recent VR devices such as the Oculus Quest are capable of tracking the user's hands without any additional devices, using 4 monochrome cameras, positioned on the corners of and facing outward from the HMD [37]. While this is a promising feature, currently the tracking works poorly when you put your hands close to each other or hide individual fingers from the camera view for a long time. While holding a smartphone, only the thumb is tracked mostly correctly. Additional study is needed to determine if the Oculus Quest's finger tracking quality is good enough to show the finger model and detect finger input during smartphone usage in VR.

Fiducial markers provide a possible option to track a smartphone in VR. Although they weren't used to track a smartphone, fiducial markers have been employed by many researchers previously for various tracking purposes [9,42,52]. A fiducial marker is a tag placed in the field of view of an imaging system for use as a point of reference or a measure. Usually, in computer vision, it is a 2D black and white image with the matrix on it (see Figure 1). Fiducial markers can be tracked using only a single camera, and there are many established approaches and libraries for tracking them. They also provide full

6DOF tracking of objects they are attached to without (typically) adding any additional weight. They are thus an attractive tracking method for 6 DOF tracking of the smartphone in VR. Moreover, the smartphone can provide the fiducial marker itself, by displaying it on a part of the smartphone screen, requiring no extra effort on the part of the user (e.g., printing/affixing a marker). Although our study used smartphone-based VR Google Cardboard with the outward-facing smartphone camera for tracking, our tracking approach could be employed in any camera-based VR HMD.

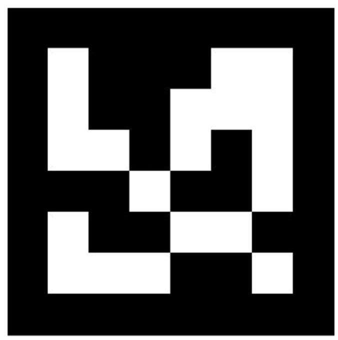

Figure 1: Fiducial marker example.

1.2 Smartphone screen translation and visualization in VR headset

The key issue in providing good real-time screen translation from the smartphone to the virtual smartphone is ensuring the lowest possible latency. Users interact with smartphone touchscreens quickly; it is essential to show them screen updates on the VR smartphone as fast as possible, as latency has a noted impact on user performance in VR systems [21,77]. The lowest-latency option to transmit imagery from the smartphone to the virtual smartphone would be to use the smartphone's USB cable. However, the screen translation should be cable-free to provide the most comfortable and ergonomic smartphone usage in VR. Thus, we instead live stream the smartphone screen over a Wi-Fi network. Previous research used the TCP protocol to send screenshots from a smartphone to a VR headset for visualization [3]. To reduce the latency further, we decided to use the relatively novel WebRTC protocol for screen streaming.

1.3 Efficient and comfortable smartphone usage in VR

We focused on evaluating various options to interact with a smartphone in VR. Users predominantly interact with a smartphone via its touchscreen, which provides both input and output functions. It is thus essential to find the best way to support both input and output on the device.

The obvious solution to facilitate smartphone *output* in VR is to translate the screen to a plane in the virtual environment in real-time. However, although VR systems often closely emulate reality, VR does not necessarily *have* to follow the same physical laws and rules as those of the real world. Therefore, while we can simulate the real world in VR, we can also enhance and make things easier and more comfortable by bending physical laws.

For example, there are different attributes we can adjust to improve smartphone usability in VR. For example, a virtual smartphone allows us to modify the screen plane size, position, and orientation in the virtual environment, or use any other transformations of the screen feed or the plane the screen image is projected onto. It is also possible to adjust the (virtual) screen resolution; it would be natural but not required to maintain the resolution as close to the real smartphone as possible, while having latency small enough to be almost unnoticeable by the user. For the screen plane size, it probably should be at least the size of the smartphone screen in the real world or bigger for comfortable usage. The virtual screen can be enlarged without lowering image quality as long as its rendered size (width and height in pixels on VR HMD screen) is lower or equal to the dimensions of the shared screen feed.

For the position and orientation of the virtual smartphone screen, two possible solutions may be appropriate. The first is to simply copy the physical state of the tracked smartphone, i.e., use a 1:1 mapping from the physical smartphone's pose to the virtual smartphone. This simulates a quite realistic smartphone usage experience and allows the virtual smartphone to effectively be co-located with the virtual smartphone, but requires a high-quality tracking system and low translation latency. The benefit of this variant is that it is natural and obvious for people to use. Also, it does not occlude much space in the virtual environment. However, there are also disadvantages to this approach. First, the resolution of all modern HMDs is much lower than the "resolution" of a human eye in the real world. Based on the data from Pirenne et. al. [66] and simple calculations, if we assume the HMD screen is 7cm in height and 7cm away from the eye, we would need around 10.5k pixels of vertical resolution to match the eye resolution with only around 53° of vertical Field of View (FOV). As a result, the presented resolution of the virtual smartphone screen in VR is certain to be much lower than that of a real smartphone screen when held at the same distance as is comfortable in the real world. Users thus will put the device closer to the eyes or lower their heads to get a better view, which may lead to physical fatigue. Second, fiducial marker-based tracking systems are not as good as infrared light-based ones. Thus, tracking the smartphone this way may yield lag or noise, which will impact the sense of presence and make it harder to look at the virtual screen.

An alternative solution is to display the virtual smartphone screen plane in front of the user, rather than co-located with the physical smartphone, while still tracking and showing the phone model according to its real-world position. This eliminates the disadvantages of co-location but may be less natural to users because of the screen and phone model separation. There is a long history of studies on co-located vs. disjoint interactions in VR [5,35,61,73,76,82].

These two solutions are examples of direct and indirect input. Indirect and direct input refers to how data or commands are entered into a system. Indirect devices require a mental translation between the human body and the machine. For example, moving a mouse forward moves a cursor upward on a screen. Direct devices have no intermediary; the movement of the body equals the input to the machine. Examples of direct devices are touch screens, light pens, and voice recognition systems.

We called the first solution Direct because it fully simulates a touchscreen of a smartphone in VR, which is a direct input device. We called the second solution Indirect accordingly, in this case, we use a smartphone more as a touchpad and have a separate screen similar to the monitor. Such a case is similar to the usage of a laptop trackpad but uses the thumb for the input.

Several previous studies have compared Direct to Indirect input conditions [27,28,40,59,74,76]. However, the results of these studies vary, depending on the input device and tasks. Therefore, it is reasonable to conduct a comparative study with these specific conditions, when both touchscreen and touchpad are simulated in VR.

Another technique that could make one-handed smartphone usage in VR more efficient and comfortable is input redirection. The touchscreen size of modern smartphones can be 5 inches in diagonal and more, which means the thumb zone covers only around half of the touchscreen [10]. Therefore, warping of the touchscreen surface and redirection of the virtual fingers may be beneficial for one-hand smartphone usage in VR. Because of the “cardboard” HMD limitation, this study is focused on touchscreen surface warping. While other techniques were proposed for thumb zone extension [84], surface warping was previously applied in VR using a tablet and a stylus with promising results [22]. Moreover, surface warping may be applied not only to reach all over the screen with a thumb but also to implement VR interaction techniques when using the smartphone as a VR controller.

1.4 Contributions

There have been relatively few studies on touch input using smartphones in VR. Only a few studies have used a smartphone as an input method in VR. There are currently virtually no mobile apps that allow using the smartphone from VR. Consider that currently using VR with a smartphone for virtually any task, such as simply answering a call, requires context switching and removing the head-mounted display (HMD). This causes the user to disengage from the VR task and increases the probability of cybersickness.

This thesis presents studies on the effectiveness of different approaches to interaction with a smartphone in VR. The current research investigates the use of a secondary smartphone as a tactile tablet-like surface used in combination with a cardboard HMD, to investigate interaction possibilities and performance capabilities offered. This research benefits VR HMD developers and users of VR systems and applications, providing insight into how to implement novel interactions in the VR HMDs. The research also benefits VR researchers because it provides information about using smartphones in VR with input/output as well as scaled tactile surfaces performance influence.

Another contribution is the investigation of the input device for the smartphone-based VR displays. Current “cardboard” VR displays (e.g., Google Cardboard) are cheap and easily accessible, requiring only a smartphone to provide an immersive virtual reality experience. They are thus promising as a hardware platform for the widespread deployment of VR applications such as education (e.g., remote learning in VR), training (e.g., surgical simulation), and entertainment. However, they offer limited interaction capabilities due to the absence of a separate “wand-like” input device provided with more full-featured devices like the Oculus Rift. While the proposed system with smartphone-based HMD may be employed only with the two smartphones available, it still has potential due to the vast popularity of smartphones. Finally, due to the ongoing COVID-19 pandemic, the study itself was conducted in a completely remote way (i.e., no physical interaction with participants). This thus adds to a growing body of literature investigating the possibilities of conducting similar remote studies in the future and gather feedback to improve such a method.

1.5 Thesis Outline

Chapter 2 presents a short review of previous researches on smartphone usage in VR as well as the use of tactile surfaces and input redirection. We also briefly explain the evaluation techniques we used, following the methods employed in previous studies. Chapter 3 contains a description and justification of used software and hardware solutions. Chapter 4 is about the users’ selection performance with different smartphone screen positioning using the proposed prototype. Chapter 5 describes the effects of the surface scaling technique on selection performance. Finally, Chapter 6 provides discussions on our insights and findings, the limitations of the proposed technique and prototype, and future work.

Chapter 2: Related Work

In this chapter, we examine previous studies which included smartphone usage in VR including the studies that inspired this work.

We cover previous work on several aspects of virtual interaction, input redirection, and interaction with physical devices in VR. Thus, we first establish some terminology. VR interaction consists of the following tasks: Selection, which involves pointing to virtual objects using an input device and activating the selection trigger. Manipulation involves changing a virtual object's position or orientation using an input device and may include grabbing, throwing, etc. Navigation involves changing the virtual camera position (i.e., usually the user's virtual character or avatar) using an input device, and may include walking around, riding a vehicle, teleportation, etc. Redirection illusions, a primary topic of this thesis, involve virtual redirection of the user's virtual hands/controllers or warping of the virtual environment to map many virtual objects to one physical object. An example of the redirection illusion may be hand location redirection: the position of the user's real hand differs from the virtual model hand position in VR. It could be used to gradually change the virtual hand movement and eventually it will grab multiple virtual objects one after another in VR, while the user grabs the same physical object in reality.

Table 1 summarizes key studies on redirected input and smartphone usage in VR. To summarize, despite the great availability and prevalence of smartphones and the well-known advantages of planar surfaces in VR, very few studies have studied the incorporation of mobile devices in VR. Moreover, few studies have used warping techniques with planar input devices, especially with finger input. My present thesis and proposed prototype aim to fill this gap.

1st Author, Year	Description	Redirection Method	Evaluation Method	Relation to the research	Main Findings	Notes
Feuchtner, 2018 [25]	A gradual shift of the user's virtual hand to reduce the physical strain	Non-linear gradual offset	Pursuit tracking task	Input redirection, benefits of Indirect input	A vertical shift of virtual hand reduced fatigue and mostly maintained body ownership	Vertical shift decreases performance by 4% and gradual shifts are preferable
Gebhardt, 2014 [34]	Evaluation of smartphone-based menu system in VR	No redirection	Experts review and user study with tasks using Mobile Menus VS Extended Pie Menus	Usage and evaluation of input using smartphone in VR	Mobile Menus were operated faster, but Extended Pie Menus was more favored	The experts saw great potential in the use of smartphone-based menu systems
Amano, 2018 [3]	System for mobile apps testing in VR with navigation and Wi-Fi networks simulation	No redirection	Quality evaluation of Access Points selection strategies	Example of implementation of smartphone-based input-output control in VR	Development and evaluation of the testbed system.	Emulation by sending screenshots of the real smartphone attached to the hand controller to the VR app
Forlines, 2007 [27]	Direct-touch vs. mouse input for tabletop displays	Control-Display gain	Unimanual and bimanual 2D target selection and docking task	Evaluation of touchscreen input with various screen distances	Direct-touch is better for bimanual tasks, but mouse may be better for single point-interaction	Users may be less accustomed to two-mice input than to multitouch
Forlines, 2008 [28]	Evaluating tactile feedback and direct vs. indirect stylus input	Offset	Pointing and crossing selection task	Evaluation of direct vs. indirect input on touchscreens	Direct input performs better in crossing selection, tactile feedback is beneficial	Tactile feedback is the most beneficial with direct input and small targets that are harder to select
Sun, 2014 [74]	Effects on the performance of analytical tools using direct vs. indirect touch input in VR	Control-Display gain	Menu/widget operation task (2D selection and manipulation)	Evaluation of direct vs. indirect input on touchscreens (tablet vs. touch-pad)	Direct vs. indirect input was not significantly different	Touch-based inputs showed significantly better results than 6DOF and 2DOF controllers' input
Teather, 2009 [76]	Display collocated vs. disjoint with tracked pen in fish-tank VR	Offset	2D selection task (Fitts' Law)	Evaluation of direct vs. indirect input on touchscreens	Direct vs. indirect input was not significantly different	Movement into the scene was faster when the display and input device were co-located
Imamov, 2020 [40]	Effects of interface position on comfort and task switching time in VR	Offset	The task was to memorize symbols appearing in different places in front of the user	Evaluation of the best position for glanceable interface in VR	Switching time increases when the information is displayed farther away. The best position is on eye level or below	Participants preferred content on medium distances while being faster with content at far distances
Kohli, 2013 [46]	Adaptation to warped virtual spaces with redirected touching	Non-linear gain (rotated interaction surface)	2D selection task (Fitts' Law) with real and virtual screen rotations	Evaluation of redirected touching using touchscreen	Participants trained similarly well in warped and unwarped virtual space after adaptation	Only 4 out of 14 were able to identify that's was caused by the orientation discrepancy
Didehkhorshid, 2020 [22]	Measured performance of stylus usage with a warped virtual surface in VR	Scale factor	2D selection task (Fitts' Law) with different warping scales conditions	Evaluation of redirected input with a warped virtual surface in VR using touchscreen	Scaled conditions were no worse when the 1-to-1 on Throughput but worse on Movement time	The experiment tested warped surface with a stylus, results may differ for the finger input

Table 1: Summary of Studies and their findings on redirected input and smartphone usage in VR.

2.1 Smartphone usage in VR

As outlined above, we can take advantage of modern smartphone features in VR. This may be especially beneficial for budget smartphone-based HMDs, which do not include any real 3D controllers. For more expensive HMDs like the Oculus Rift, Oculus Quest, and HTC Vive it would be convenient to be able to use a smartphone (e.g., to answer calls or messages) without the need to remove the headset. This would likely improve immersion and presence as well. Finally, VR interaction using a planar surface (such as a touchscreen) as an input device may be beneficial for selection and manipulation efficiency in some cases [43,47,51].

Amano et al. [3] used VR as a testbed for smartphone applications. Specifically, they tested that Wi-Fi hotspots can provide a continuous Internet connection while the user is moving in the city. A navigation map was shown on the smartphone screen so the user can better understand the current location on a virtual street. The authors hypothesized that testing in VR is sometimes more cost-effective than conducting tests in the physical world. Their system builds the real-world environment in 3D space and real networks in VR using the existing 3D city models and Wi-Fi database. Moreover, they cast the user's smartphone screen in VR in real-time and attached an HTC Vive controller to the smartphone, to be able to track it in 6DOF. The system was capturing the screen of the smartphone and streamed it to a PC via USB. The PC then captured the received screen and forwards it to the browser inside the VR application. Such tracking and casting methods have disadvantages described previously in the Introduction section. Hence, the authors reported 695.5ms and 729.0ms of the average and maximum delay time respectively, which is around three times larger than we achieved using WebRTC protocol. Thus, such a system can be used to test only for a system with little or no touchscreen input and rapidly changed output. While this may be sufficient for the navigational maps in the presented research, such latency levels can hardly be appropriate for highly interactive apps.

Another option to operate a physical smartphone in VR was implemented by Bai et al. [8]. In their system, the authors attached a VR controller to the phone's header (with the handle attached to the back of the phone and the tracking circle above it) for pose tracking and attached a depth camera to the VR headset's front panel for capturing hand gestures. The system showed the user's hand in VR with partial transparency to avoid occluding objects in the virtual environment. The smartphone's display was mirrored in real-time in VR as well. While the authors did not specify how they mirrored the screen in VR, they reported using a private network connection with a 170 ms average delay. The authors conducted two user studies. In the first study, participants performed common smartphone tasks in both VR and reality: video calls, instant messaging, social networking, media consumption, and photography. User preference questionnaires results were significantly better for reality. Of the VR conditions, calling and photography had the highest subjective preference scores while typing instant messages had the lowest. This result was likely due to imprecision and lag when typing on a virtual smartphone keyboard in VR. In the second study, they compared text entry of characters and words in reality and VR, with different virtual hand conditions and varying degrees of the virtual hand model transparency. While the reality condition was again significantly better, there were no significant differences in accuracy and speed in other conditions. Overall, the utilization of a depth camera for hand tracking is a promising technique for such a task. It will be possible to use a similar approach with smartphone-based cardboard VR should smartphones be equipped with depth cameras in the future.

Other studies used a smartphone in VR as an input device only. Gebhardt et al. [34] used a smartphone as a menu system input in a VR application presented in a VR

CAVE, thus did not have to implement tracking and screencasting. The smartphone contained only a menu to interact with, and, as the CAVE did not have an HMD, the users were selecting menu items on the real smartphone. The implemented system used WebSocket protocol to exchange messages between a VR application and a smartphone. The authors performed an expert review first and then conducted a study to test user acceptance of the menu system. The experts tested the menu system in two different roles: a presenter who gave a VR presentation to a visitor of the presentation. The menu had a different set of menu commands for each role and sets of tasks to perform. The experts filled out concluding questionnaires after the study. Novice users also went through the same procedure. While experts appreciated the system, user acceptance was lower than expected. Menzner et al. [60] compared an above surface interaction technique with traditional 2D on-surface input for map navigation in VR. The system used a smartphone as a surface and tracked both smartphone and user's fingers with an OptiTrack optical tracking system. Results showed that the interaction above the surface offered significantly better performance and user preference compared to pinch-to-zoom and drag-to-pan in planar information spaces navigation. However, the smartphone and finger tracking used in this study are impossible to implement without an external tracking system and physical markers.

Overall, while there are past studies both on default smartphone features integration in VR and using smartphones as a tool to improve VR experience, no commonly accepted technique has been established yet. Due to variety of the smartphone in VR usage in the reviewed research, results are difficult to compare.

2.2 Direct and Indirect input

Input controllers sense a given property and convert it into data that are transmitted to the host computer for processing. For pointing devices, the most common properties sensed are position, displacement, and force [57]. Examples of position control devices include graphics tablets and touchscreens. Displacement-sensing devices include computer mouse and laptop touchpad. The best example of force-sensing devices is the analog joysticks on some game controllers. Input devices also differ in an order of control, i.e., how the input is mapped to software. They can control cursor position (mouse, laptop touchpad) or velocity (joysticks). Previous work [86] determined that position control is best applied with a position-sensing device and velocity control is best applied with a force-sensing device. Finally, control-display relationships can be divided into natural and learned. Natural mappings do not have a spatial transformation between the control motion and the display response, i.e., the mapping is 1:1. While a natural relationship is not necessarily more efficient, it is easier to understand, especially for users from different cultures, which is a benefit. We call such input *direct*, and the device which employs it – *direct input device*. Consequently, we call input *indirect* if a spatial transformation does take place. A touchscreen is example of direct input device (e.g., the input triggers where your finger located). In contrast, a mouse is an example of an indirect one (i.e., mouse movement on a horizontal plane is transposed onto a vertical plane of the screen, requiring a spatial rotation and scaling).

Smartphone touchscreens usually employ position sensing mapped to position control. While it is possible to implement displacement control (a prototype with such control was used to increase the thumb zone [84]), it is less natural. All techniques used in our studies employ position-sensing input with position-control mappings, the same as a default smartphone's touchscreen input. However, due to presenting the smartphone in VR and space warping, they are much less natural than using the smartphone in the real world. However, we are more interested if the co-location of the real touchscreen and virtual smartphone screen position (i.e., direct condition) is necessary: does this co-location make the input more efficient than when input and output interfaces are dislocated (indirect condition)?

Psychologists have long studied decoupling of input and action, via the optical displacement of physical objects using prisms. Prism adaptation is a sensory-motor adaptation that occurs after the visual field has been artificially shifted laterally or vertically. It was first introduced by Hermann von Helmholtz in late 19th-century Germany as supportive evidence for his perceptual learning theory [64]. Studies have shown that humans quickly adapt to these sensory-motor transformations, to the point of having to adapt back to normal after the displacement ends [6,24,50,83]. Prism adaptation has been researched in detail with VR headsets instead of prism lenses [1,11,20,31,32]. Experiments results suggest that even in VR, people adapt to virtual versus real body and objects mismatches, one of which is the indirect condition.

Studies comparing direct and indirect input devices have yielded sometimes conflicting results in different usage scenarios. Forlines et al. [27] conducted an experiment to investigate the differences between direct-touch input and mouse input on tabletop displays. They found that users benefit from direct-touch input on bimanual tasks. However, results also showed that mouse input might be more appropriate for single-point interaction. Forlines et al. [28] conducted another study in pointing and crossing (move cursor over vertical bars) selection tasks using stylus input with direct and indirect conditions. In the direct condition, stylus input and display were co-incident (touchscreen). In the indirect one, stylus input (trackpad) and display (monitor) were separated (cursor was displayed on a monitor, controlled by stylus input in trackpad, similar to the mouse). They compared direct and indirect options for both tasks and found that while direct input was significantly more efficient in crossing selection, the result was equivalent in point selection. Other research indicated that older adults were more influenced by the input device choice [59].

Sun et al. [74] compared two 6DOF input devices with two 2DOF ones in an immersive virtual environment (CAVE system). The 2DOF devices were touch-based with a display screen (Direct) and without it (Indirect). They found touch input is comparable with 6DOF devices for visually demanding tasks. However, they did not find any significant difference between the direct and indirect conditions.

Teather et al. [76] used a tracked stylus to compare direct and indirect conditions in fish-tank virtual reality, a small-scale VR system using a stereo 3D monitor. Participants performed 3D object selection tasks. The researchers found no significant differences between the conditions in general. However, the results indicated some benefit in the direct condition in object movement in specific directions. Finally, Imamov et al. [40] examined and compared the different world-locked positions of an information display in VR. They found that context switching time increases if the information was displayed far from the task position. Participants found more preferable content that was placed at eye level or below, and that was positioned at medium distances.

Using a smartphone in VR provides a haptic interface for the user to interact with objects in a virtual environment. Introducing mismatches between the physical and virtual screen plane positions and employing surface warping are examples of input redirection. We further focus on other types of input redirection, which include redirection of virtual body parts or haptic objects (haptic retargeting) in VR. Haptic retargeting in VR can be implemented either by body warping or world warping or their combination. The idea of body warping is to offset the rendering of a virtual limb (typically the virtual hand) from the tracked physical position of the real limb. This modifies the mapping between the real and virtual worlds. World warping techniques, such as the approach of Azmandian et al. [7], rotate the immersive virtual environment to align real and virtual objects [85]. Redirected input is often combined with haptic retargeting. Azmandian et al. [7] conducted a study, where participants built a virtual castle by arranging and stacking multiple virtual cubes mapped to a single physical cube. Haptic retargeting was applied to redirect the user's hand to repeatedly grasp the same block. This creates the illusion of multiple tangible cubes in the VR environment, despite only a single physical cube being used. They found that the highest presence and satisfaction scores were achieved with the combination of body and world warping.

Han et al. [36] compared two remapped reaching techniques: static translational offset between the virtual and physical hand before a reaching action and one that dynamically interpolates the position of the virtual hand during a reaching motion. While the static offset simply makes the virtual hand appear to be a constant distance from the real hand position, the dynamic offset gradually moves the virtual hand toward the selection target. The dynamic offset employed in the study is similar to the popular Go-

Go interaction technique proposed by Poupyrev et al. [68]. The results showed that the static translational shift performed better than the dynamic one and was more robust for situations with larger mismatches between virtual and physical objects.

Cheng et al. [19] implemented a system that predicts a user's hand movements based on their eye gaze. Their goal was to mitigate the primary limitation of haptic retargeting: to apply retargeting to the desired object, one must know which target the user will reach for in advance. The system was able to predict touch intentions with 97.5% accuracy. Results showed that the maximum angle acceptable for retargeting a user's hand is 40°. Feuchtner et al. [25] proposed an interaction technique called Ownershift to reduce the physical strain of overhead interactions. An interaction with a virtual object begins with 1:1 mapping. If the interaction is prolonged, the virtual hand space is shifted gradually, guiding the user's real hand into a more comfortable position. Thus, the user can continue to interact with an overhead object with reduced strain. The authors evaluated the technique and found that it significantly reduces the physical strain, while only slightly reducing the sense of body ownership of the virtual hand and task performance.

Overall, the results of studies on decoupling control and display spaces in VR suggest little difference between direct and indirect conditions, consistent with the prism adaptation research [1,11,20,31,32] mentioned earlier. In the two studies by Forlines et al. [27,28] that did find the significant difference, it was most probably not due to the screen dislocation. The first paper [27] found significant benefit from direct touch in bimanual tasks compare to the mouse input, which is reasonable since the mouse is designed for one-hand usage. In the second paper [28], a significant result was found in the crossing task because the stylus was coming out of the trackpad tracking range. The authors evaluated discrete and continuous types of stylus contact and the main influence on the differences between the direct and indirect conditions had a discrete type. This seems to be because the discrete type required users to lift the stylus from the trackpad, which eventually leads to situations where the stylus leaves the tracking zone. To our knowledge, no input redirection techniques have been applied to smartphone input in VR, which makes it an open area for research. Since there is some inconsistency in the results of previous research on redirected input in VR, it is unclear how redirected input on smartphones in VR will work. We thus argue that our study will be useful both for future research in this area as well as commercial VR solutions.

2.3 Effects of Scale on Selection Performance

The type of input redirection we employ in our study is surface scaling: making a virtual surface appear physically larger than the corresponding physical surface [22]. The idea of surface scaling is very similar to well-known Control-Display gain (CD gain). CD gain describes the proportion between movements in the control space to the movements in the display space. Modern OSes change CD gain based on the current mouse speed. When mouse speed is fast, the CD gain goes up to cover long-range movement faster and when mouse speed is slow CD gain goes down to improve selection precision [15]. The same is true for trackpads. However, CD gain is usually not applied on devices with a touchscreen, like smartphones and tablets since all input already has 1-to-1 mapping. Using rate-control mapping on a smartphone will create an inconsistency between finger position and real input point, which will make the input less natural and harder for users to adapt to. Moreover, the user's hand and fingers may sometimes block the real input position point (cursor), which may decrease the comfort of usage and efficiency. Both such limitations are not a problem in VR. Adjusting the rendering of the virtual hand/finger (if needed) and warping a planar surface can mitigate both limitations, while virtual hand/finger transparency or disabling hand rendering will fully fix the occlusion problem. Finally, CD gain can be applied in VR to effectively increase the size of an interaction surface – which is potentially useful, since you can have a small tactile surface (e.g., smartphone, smart-watch) behave like a larger virtual surface. Among various possible applications, such CD gain (or surface warping) can be crucial for the one-hand smartphone input to increase the thumb-zone without drastically decreasing efficiency.

There are several studies performed with a warped input surfaces in VR. Kohli et al. [45] implemented a virtual board that was oriented differently than the real board providing passive haptic feedback. The authors compared the one-to-one condition with the real board at various angles. The authors used the standard Fitts'-law reciprocal tapping task [26,75] on the board positioned in front of the user on a table on arm level. Participants tapped targets using their right index finger tracked by a PhaseSpace optical motion capture system. Statistical results indicated that selecting warped targets was no worse than selection without scaling (1-to-1). However, results also showed a significant difference in movement time and authors were unsure about if a 1bps indifference zone is acceptable. In their next study [46] the authors evaluated training and adaptation in a real versus virtual environment. They divided the experiment into Pretest, Training, and Posttest phases and measured the efficiency difference between Training and Posttest phases. The authors have done it both with the touchscreen without VR and using HMD with unwarped and warped (18°-degree rotated touchscreen) conditions. Results indicated that virtual training was less effective than real-world training, but after adaptation, participants trained no worse in a warped virtual space than in an unwarped one.

Didehkhorshid et al. [22] proposed a surface warping technique called warped virtual surfaces (WVS). With WVS, the position of a cursor is determined by the physical input position relative to the center of the screen multiplied (both X and Y coordinates) by a scale factor. We employ this technique in the current study and thus describe it in greater detail in section 3.4. The authors used a stylus with a tracked drawing tablet in VR for input and performed a Fitts' law selection task to evaluate performance with different scale factors (from 1-to-1 mapping to 2.4 scale factor). The study revealed that, while movement time was significantly different, the performance in terms of throughput and error rate was no worse than a 1-to-1 mapping. The results are similar to what Kohli et al. [45] found, which is the reason to suspect that scaling does not impact performance very much, at least for the small-scale factors. Such results are evidence of the applicability of the WVS technique in VR applications. One of the goals of our study is to verify if the WVS technique would show the same results with a more widespread finger input with a smartphone.

2.4 Fitts' Law

Since we employ Fitts' law selection task in our study, it is briefly described here. Fitts' law predicts target selection time as a function of target size and distance [63]. The model relies on these equations:

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

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

Equation 3 $\boldsymbol{A_e = \frac{\sum_{i=1}^{N} A_i}{N}}$

Equation 4 $\boldsymbol{W_e = 4.133 \cdot SD_x}$

In Equation 1 *MT* is movement time, and *a* and *b* are empirically calculated via linear regression. The *ID* is the index of difficulty (the overall selection difficulty), based on the amplitude *A* – the distance the cursor travels to select the target, and *W*, the target width (i.e., target size). As can be seen, we may increase the index of difficulty by increasing the amplitude and/or decreasing the width of the target.

Equation 2 presents throughput *TP*, which combines speed and accuracy and is unaffected by the speed-accuracy trade-off commonly seen in such tasks [55]. ID_e is the effective index of difficulty and gives difficulty of the task users actually performed, rather than that they were presented with. It is thus widely used and recommended by the ISO 9241-9 standard as a primary metric for pointing device comparison. In contrast, metrics like selection time or error rate are less reliable and inconsistent between studies, as they will vary with individual participant biases towards speed or accuracy. Throughput has been shown to be more stable in both 2D and 3D selection studies [14,72,78,79].

Equation 3 presents effective amplitude, A_e, the mean movement distance between targets for a particular condition. Finally, in Equation 4 we have a standard deviation of selection endpoints projected onto the vector between the two targets – SD_x. It incorporates the variability in selection coordinates and is multiplied by 4.133 to get effective width W_e. This effectively resizes targets post-experimentally, such that 96% of selections hit the target. This process normalizes the experimental error rate to 4%. This accuracy adjustment facilitates the comparison of throughput scores between studies with varying error rates by first normalizing accuracy [56]. 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.

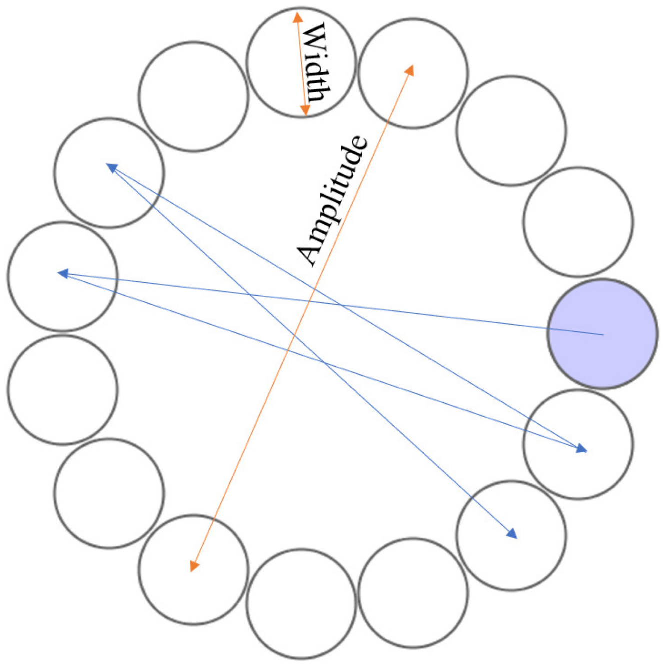

Figure 2: Fitts' law task, arrows indicate where the target would move after each selection.

2.5 Equivalence testing

Finally, we discuss equivalence statistical testing, which we employ in our analysis of the first study. Equivalence testing is a type of statistical equivalence test that shows if conditions are statistically equivalent. In contrast, more commonly used null-hypothesis statistical tests (NHST) can only reveal differences between conditions (i.e., they cannot indicate if two conditions are statistically "the same"). If the efficiency of the conditions is equivalent, we may consider using the condition, which is easier to implement or has other advantages. That's why we employ equivalence testing in addition to NHST. Equivalence testing requires defining an indifference zone, i.e., the maximum allowed difference between two conditions to be considered equivalent based on the context of the study [70]. A two one-sided t-test (TOST) is used to make this determination.

After defining the indifference zone, one must analyze the mean difference between the conditions and the 2-tailed 90% confidence interval (which is equivalent to two one-tailed 95% intervals in opposite directions) of that difference. Finally, we check if the mean difference score and the 2-tailed 90% confidence interval fall within the extents of the indifference zone. If so, then the two conditions are deemed to be equivalent [70]. 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: Software and Hardware Prototype Description

In this chapter, we describe the software and hardware we used for the prototype and user studies. We also explain the rationale for choosing specific system components.

3.1 Hardware

While the proposed method for presenting a smartphone in VR could be implemented using almost any HMD, we decided to first experiment with Cardboard VR[9]. Cardboard, first popularized by Google, is a small cardboard HMD that requires the user to insert their smartphone. The smartphone acts as a display, and its sensors support head rotation detection. There are two reasons for using this HMD in our study.

The main reason why we conducted the user studies with Cardboard VR is the ongoing COVID-19 pandemic. Our studies were conducted when social distancing was a priority. Fully remote studies were much easier and safer to conduct to ensure the complete safety of the participants and experimenter. Using a Cardboard VR headset with the participants' smartphone was a good option to conduct the study in such a manner, avoiding the necessity to send, recover, and sanitize expensive VR equipment (e.g., Oculus Quest/Rift HMDs, supporting PC, etc.). The Cardboard HMD is relatively cheap, which allowed us to send it to participants both as a tool for the study, but also as a reward for participation in the study; participants kept the Cardboard that was sent to them upon completing the study.

There are other reasons why smartphone-based VR HMD is an acceptable choice for our study. Cardboard VR is the cheapest and therefore most accessible VR headset today. Such devices have lower resolution and usually do not provide or support any

[9] https://developers.google.com/cardboard

additional controllers, unlike more expensive dedicated head-mounted displays like the Oculus Rift. This generally leads to a worse VR experience compared to the more expensive products; the user is limited to very simple interaction capabilities (e.g., looking around an environment, no hand-based interaction, limited navigation). As a result, any interaction technique that can be used with Cardboard VR to improve interaction possibilities without significantly increasing the cost (provided the user has a second smartphone) would yield a marked improvement to the usability of such devices. Moreover, because of their low cost and accessibility, such devices are well-positioned to become predominant head-mounted displays in the future, should they offer interaction possibilities comparable to conventional head-mounted displays. Photos of the Cardboard HMD we use are seen in Figure 3.

Finally, the proposed system needs 2 smartphones to operate. One of them has to be put in the Cardboard HMD. The smartphone acts as HMD and tracks the second smartphone with the camera at the same time. We called the first device Smartphone for VR view (SVR). The second smartphone is needed for user input and is called Smartphone for Hand Input (SHI). SHI has an app to provide participants with selection tasks and record their performance data, and another app to transmit the screen feed to SVR via Wi-Fi. SHI also has a fiducial marker displayed on the upper part of the screen for tracking purposes.

The main limitation of the hardware solution of the prototype is that not everyone has 2 Android smartphones, some people sell or giveaway their old smartphones and a lot of people use iPhones. However, the prototype can still be employed if users can borrow the second smartphone from people they live with.

Since the study was conducted fully remotely, participants used their own smartphones. That is the reason why participants used different smartphones. Full lists of smartphones employed in both studies can be found in sections 4.3 and 5.3.

Figure 3: Smartphone-based VR HMD used in both user studies – VR Shinecon Box 3D model DV626-9686f from different angles.

3.2 Software

We decided to use the Unity game engine and Android Studio IDE for the prototype development, as they are free for personal usage and are standard development tools for VR and Android applications [3,22,39,60,88]. The prototype supports Android OS only for the purpose of installation simplicity. The system consists of three applications:

1. **VRPhone**: This app runs on the SVR. This presents the virtual environment seen by the user during the experiment, with the translated screen of the second smartphone in it.
2. **FittsStudy:** This app ran on the SHI. It contains a study configuration setup, presents the targets to be selected by the user, and gathers data logs about the selection performance.
3. **RTC app:** This app is also on the SHI device. This translated the smartphone screen from the SHI device to the SVR application (presenting the copy of the screen on the virtual smartphone) via a local Wi-Fi network.

All project source code and assets are available on GitHub[10]. Detailed information about each application follows.

3.2.1 VRPhone application

We used the Unity game engine for the VRPhone development. The application provides four main features:

1. Presenting a virtual environment in "cardboard" mode, using split-screen for the stereo rendering of the eyes and smartphone sensors to rotate the camera.
2. 6DOF tracking of the SHI device in real-time (via fiducial marker displayed on the SHI screen) and showing corresponding virtual models with the same position and rotation. The fiducial marker is seen in Figures Figure 4 and Figure 5 on the top half of the virtual smartphone.
3. Scanning a QR-code displayed on the SHI device provided by the RTC application to establish a WebRTC connection between the two devices.

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[10] https://github.com/Staskkk/VRPhone

4. Receiving the SHI device screen feed and other parameters and showing a virtual screen on top of the virtual model or in front of the user depending on the task condition.

In Figure 4 and Figure 5 you can see the screenshots of the app during the study.

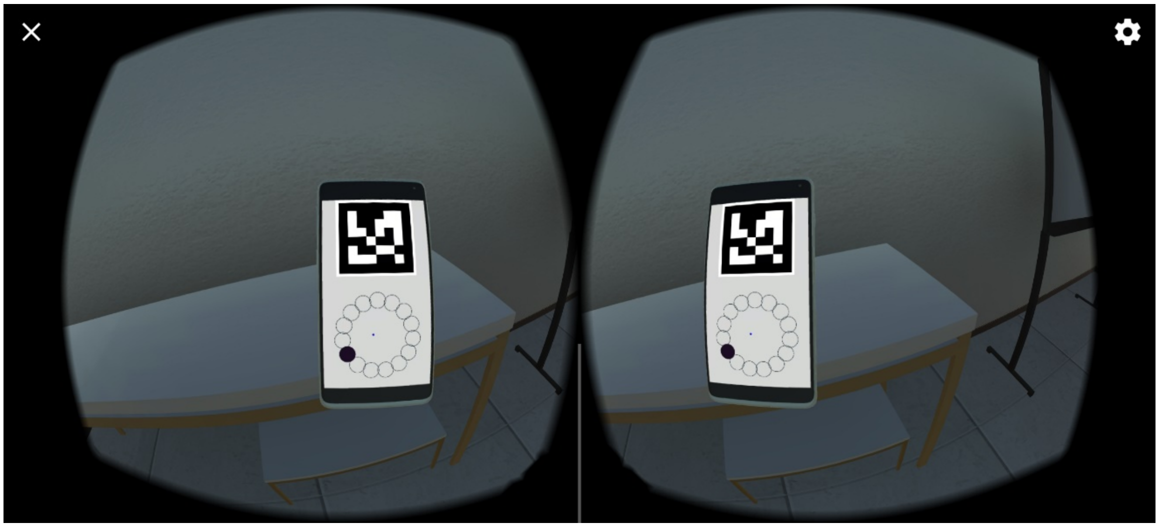

Figure 4: VRPhone application screenshot during the selection task study in Direct mode.

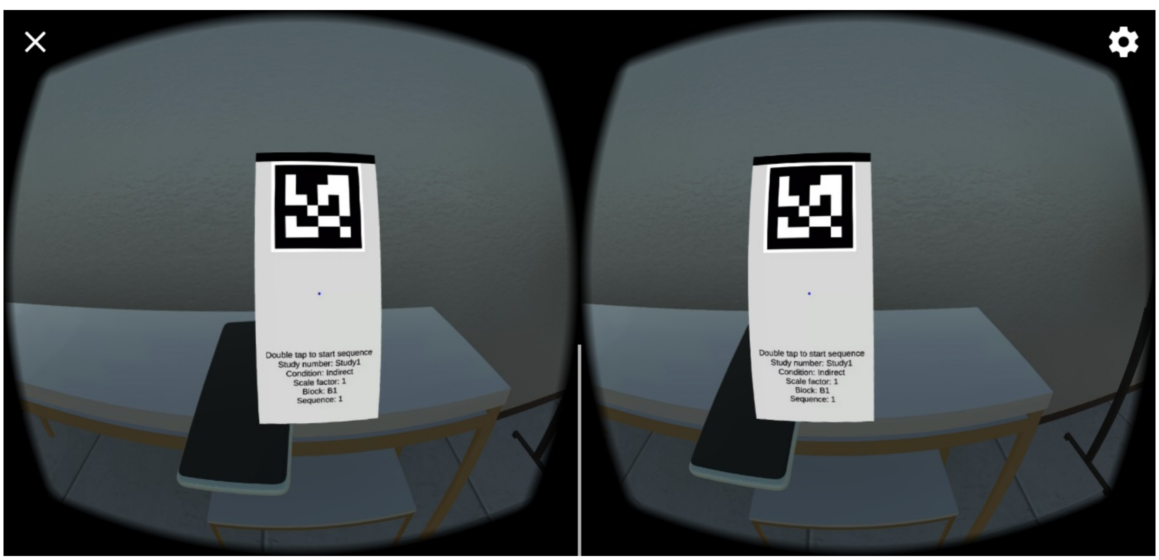

Figure 5: VRPhone application screenshot during the selection task study in Indirect mode. You can see the virtual smartphone model tracked and rendered behind the screen.

3.2.1.1 Main features description

Full 6DOF smartphone tracking was done by SVR camera tracking the fiducial marker, showed on the screen of SHI (via Fitts application). To improve the rotation tracking, SHI sent its gyroscope orientation data to SVR, and SVR applied the data to the virtual model, relative to the last rotation based on camera tracking. Camera tracking rotation had priority over the gyroscope data, therefore gyroscope relative orientation was applied "between" the updates from the camera tracking. Smartphone screen feed and gyroscope data were sent via WebRTC protocol with the UDP transport layer. Study-related data (condition, etc.) was sent via WebRTC with the TCP transport layer.

The app supported two screen position options or conditions: Direct and Indirect. Both conditions have a virtual model of a smartphone rendered in VR at the position of the real smartphone. However, the difference is at the rendering location of the virtual screen:

1. Direct condition – the virtual screen was rendered on top of the virtual smartphone model – in the same fashion as a real smartphone. The direct condition cannot be implemented without the 6DOF tracking of the real smartphone.
2. Indirect condition – the virtual screen was rendered at a constant position above the virtual table, slightly below the user's eye level. The screen floated in space (not following the user view). However, the screen always rotated around its vertical axis to orient itself facing the user. The virtual model of the smartphone showed a black screen – to show the place of the real smartphone and its touchscreen. We decided to keep showing the smartphone virtual model in

Indirect mode during the studies (to keep the smartphone GPU and CPU load on a similar level for both conditions). However, this feature is optional and helpful to the user only when picking up the smartphone. Rendering of the smartphone virtual model during smartphone usage in VR can be disabled along with the camera tracking – which would significantly decrease heat and battery usage of the smartphone.

3.2.1.2 Used libraries and implementation challenges

For the "cardboard" display mode we used "Google VR SDK for Unity"[11] – a free SDK for VR Cardboard app development provided under MIT license. At the time of development, a new version of the library "Google Cardboard XR Plugin for Unity" was released, however, we were unable to modify the new version to support upside-down SVR screen orientation. We needed to support an upside-down orientation of the SVR device in order to have the smartphone camera located on the right side of the HMD. We empirically found that this greatly improved fiducial marker tracking when the secondary tracked smartphone was held in the right hand. To mitigate the smartphone tracking shift, which happens, because the smartphone camera is located not in the vertical center of the smartphone, we implemented a corresponding shift, which also depends on the current screen orientation.

Another issue we faced when using the Google VR SDK was gyroscope drift. The library uses relative orientation tracking rather than absolute orientation tracking. This gradually yields a large horizontal shift of the environment after about 10 minutes of continuous usage. For example, the table model, which was initially presented in front of

[11] https://github.com/googlevr/gvr-unity-sdk

the user will drift to the left. We resolved this issue with a script that stored the initial compass offset from magnetic north upon starting the program, and then rotates the camera object to compensate, keeping the shift constant. These small rotations are unnoticeable by users.

For the virtual environment, we created a small lab room with a table in front of the user and some furniture around the room. For the virtual smartphone model, we used a Samsung Galaxy S10, which we obtained for free from the TurboSquid website[12] with allowance for academic usage.

While developing the prototype, we tested several marker-tracking libraries to determine which worked best for our purpose of tracking a secondary smartphone. Specifically, we experimented with the Google AR Core[13], Vuforia[14], and SolAR[15] frameworks. The marker-tracking system in AR Core was intended for use with markers placed on walls or the floor, and larger in size that can fit on a smartphone screen. As a result, tracking quality with AR Core was not acceptable. When testing Vuforia, we found it only uses static markers in the free version, and only provided dynamic/moving marker support as a paid premium feature. However, the SolAR framework, which is based on the widely known OpenCV[16] library offered robust marker-tracking performance for a smartphone. Consequently, we integrated the SolAR tracking library into the VRPhone project.

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[12] https://www.turbosquid.com
[13] https://developers.google.com/ar
[14] https://developer.vuforia.com
[15] https://solarframework.github.io
[16] https://opencv.org

The SolAR framework tracking sometimes loses the marker, which introduces smartphone virtual model motion lag. To mitigate this lag, we also constantly send the SHI gyroscope data via the WebRTC UDP data channel. After conversion to the requisite Unity format, this gyroscope data provides the virtual model orientation when the fiducial marker tracking is lost, and between rotation updates from the SolAR framework (the framework rotation updates have priority over the gyroscope data). Gyroscope data is used relative to the last rotation tracked by the marker-tracking library. An absolute gyroscope orientation was not used because of the noticeable shift between SVR and SHI compass values and their measurement errors.

For the QR-code scanning, we showed the smartphone's camera feed on the screen with an overlay hint at the start of the app. The scanning feature was provided by the ZXing library[17] (Apache-2.0 license).

To communicate with the RTC application via WebRTC we used the MixedReality-WebRTC library[18] from Microsoft (MIT License). More information about the communication between apps is detailed in the RTC application section.

3.2.2 Fitts application

The Fitts application is based on an existing Unity project FittsLawUnity[19] by Hansen et al. [38] provided with a BSD-3-Clause license. The project includes Fitts' law reciprocal selection task for different input devices such as a mouse, eye gaze, joystick, etc. We modified the code to include finger input support, made adjustments to the logs, study configuration settings, and add Android OS support. The app sends the display condition

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[17] https://github.com/zxing/zxing
[18] https://microsoft.github.io/MixedReality-WebRTC/index.html
[19] https://github.com/GazeIT-DTU/FittsLawUnity

parameters to the RTC app via the Android Broadcast method. We shifted the center of the target's circle lower to make it appropriate for the one-handed input. To be able to track the device during the study, we incorporated a fiducial marker image on the upper part of the screen. Finally, we implemented a script that emailed data logs to the experimenter at the end of the study. Figure 6 depicts screenshots of the app configuration menu and after the connection in the Direct condition (the configuration was used for practice runs only, conditions during the experiment were applied based on Participant Code).

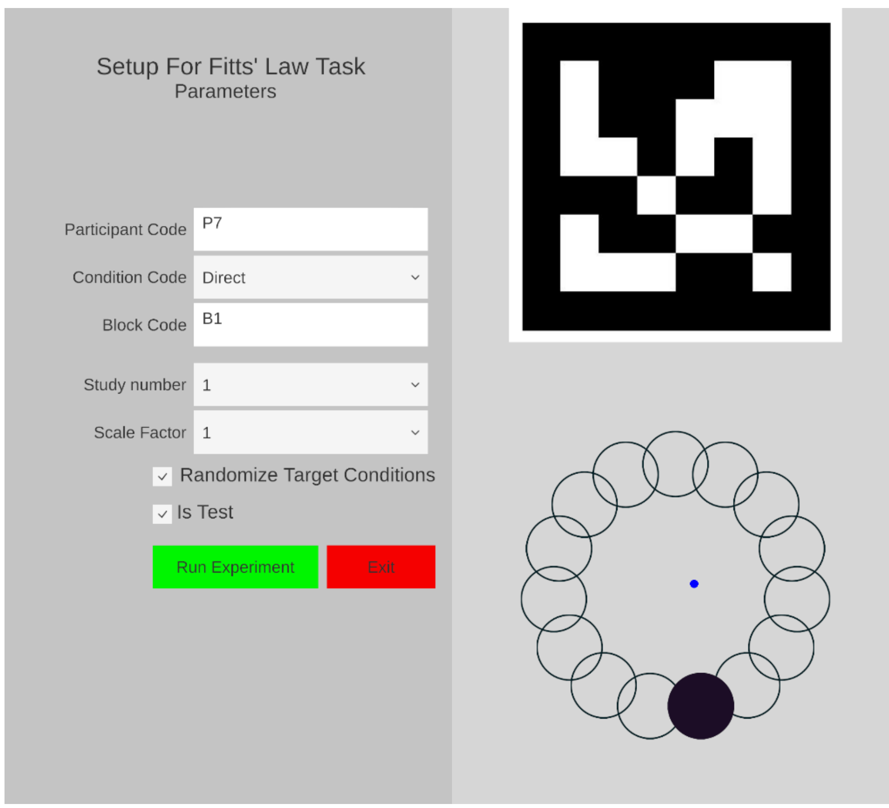

Figure 6: Fitts application screenshots: left – study configuration menu, right – study execution, you can see a fiducial marker presented at the top of the screen to support tracking of the SHI device.

3.2.3 RTC application

Since the RTC app did not require graphics, we decided to develop it using the Android Studio IDE instead of Unity to make the project smaller and increase compilation speed.

To accelerate the software development process further, we found a ready-made solution for screen-sharing on Android via WebRTC to modify for our project. Among several projects, we chose the ScreenShareRTC project[20] submitted to GitHub by a user named Jeffiano under the Apache-2.0 license. We translated the screen with 1280×720 pixels resolution, which was enough to clearly render the screen in SVR and minimize the latency at the same time.

We first tried to send screenshots of the smartphone via pure UDP packets and compared them to WebRTC performance. The WebRTC protocol with Android screen-capturing features greatly outperformed screenshots and the UDP method which was used in another study [3]. WebRTC protocol requires a signaling server to establish communication between endpoints. While both ScreenShareRTC and MixedReality-WebRTC projects were made to work with a separate signaling server hosted on Node.js, such a solution is needless for LAN communication. Therefore, we implemented a signaling server in the RTC app as a separate service and used the ZXing library (same as in VRPhone) to create a QR-code with the IP address of the smartphone. SVR with VRPhone app running then may scan the QR-code to establish the communication. Figure 7 is the app screenshot after the screen-casting permission is granted.

[20] https://github.com/Jeffiano/ScreenShareRTC

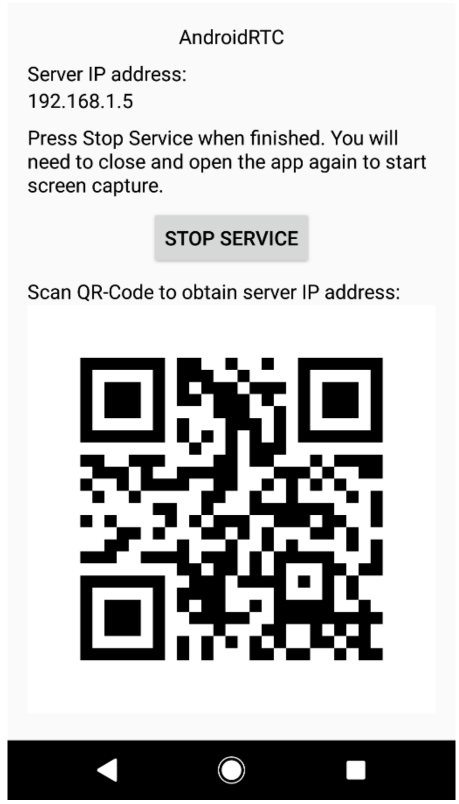

Figure 7: RTC application screenshot – QR-code contains the IP address of the device.

3.3 Latency

We measured the latency of the screen translation by making a 60 FPS video with both smartphones' screens when the SHI screen is translated to SVR via WebRTC (with UDP as a transport protocol). We selected targets on SHI with a stylus to have a better view of the moment when the targets were selected. We put SHI and SVR close together to record both simultaneously with a single camera. We then analyzed recorded video frame by frame to obtain the latency between 12 selections. Examples of analyzed video frames, which also show our setup for the latency experiment can be found in Figure 8. We measured two delays – the time when the stylus crossed the border of the target and the system registered selection (i.e., the target circle becomes empty) on the SHI device and the time from when the selection was registered on SHI to the registered selection on

SVR. We called them system latency and cast latency respectively. The sum of these two values gives us the total latency. We measured the latency in such a way with three smartphones operated as SHI and SVR in turn: Samsung Galaxy S10, Xiaomi Mi 10T Pro, and Sony Xperia X. Average system latency equaled 150ms, average cast latency was 193ms which gave us 343ms total latency. Overall, such delay was noticeable but not severely influencing users' comfort and performance.

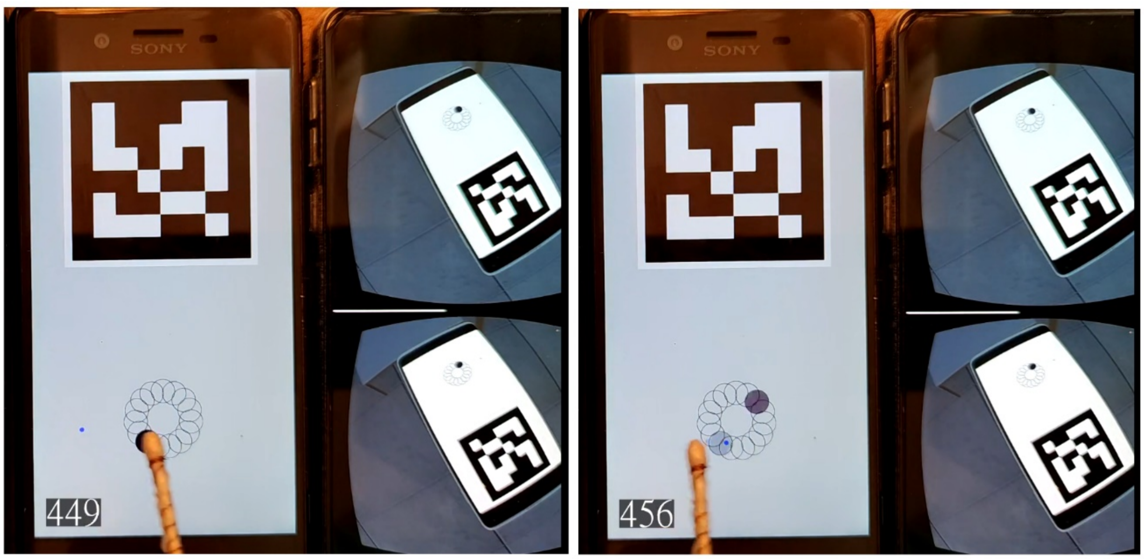

Figure 8: Two frames from the video used for latency measurement. The frame number is written in the bottom left of the frame.

3.4 Warped Virtual Surfaces

Warped Virtual Surfaces or WVS is a technique for warping planar virtual surfaces proposed by Didehkhorshid et al. [22]. We implemented the technique in our second study, therefore the technique is described here to simplify our paper understanding. In short, the method is just a linear proportion based on Scale Factor (SF) relative to the origin point. When SF equals 1, the system represents 1-to-1 mapping.

WVS allows users to interact with the arbitrary-sized virtual surface. The physical interaction space or touchscreen is always the same (e.g., the size of the touchscreen or other real bounds to touch input). A virtual surface in VR is rescaled relative to the physical world input plane. Therefore, some of the targets may be rendered outside the bounds of the real rectangular tracking area. Figure 9 represents the default usage of the system and Figure 10 shows how it was used in our study.

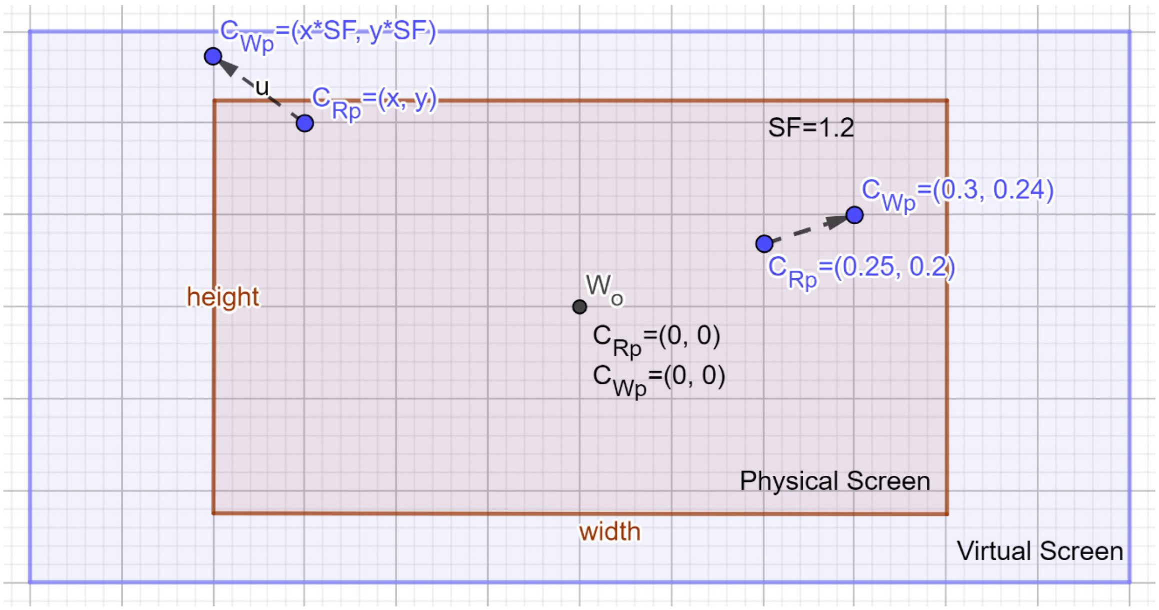

Figure 9: Visual representation of the WVS system.

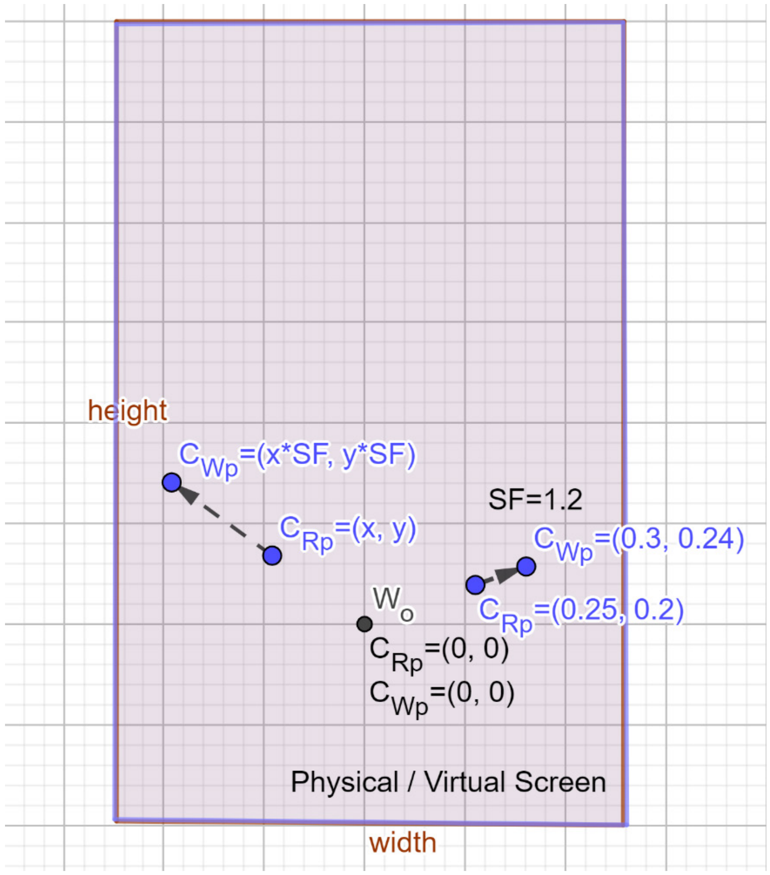

Figure 10: Implementation of the WVS system in our study.

The touchscreen usually gives us the coordinates of the user's input (C_i) relative to the top or bottom left corner (i.e., the coordinate origin of the tracking area). In our case, the coordinate origin was in the top left corner. To use the technique, we first choose the warped origin (W_O) position. In our case, we put Wo in the center horizontally and on ¼ of screen height lower when the vertical center, for the selection targets to be in a thumb-zone. Next, in each frame, we subtract coordinates of the W_O from the C_i and divide the x and y coordinates on width and height respectively to get real cursor position (C_{R_p}) coordinates in the range from -0.5 to 0.5 (or from -0.25 to 0.75 for the vertical axis in our case). It is shown in Equation 5. Finally, we multiply each coordinate by the SF to get the virtual cursor position (C_{W_p}) using Equation 6. It is clear from the equations, that when SF differs from 1, the only point where C_{R_p} and C_{W_p} occupies the same spot is W_O.

$$\textbf{Equation 5} \quad \boldsymbol{C_{R_p} = \left(\frac{1}{width}, \frac{1}{height}\right) \times (C_i - W_O)}$$

$$\textbf{Equation 6} \quad \boldsymbol{C_{W_p} = ScaleFactor \times C_{R_p}}$$

Warping the panel's surface causes C_{W_p} to move ahead of C_{R_p} as users move the stylus further away from W_O. C_{W_p}'s movement behavior 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. A larger SF would cause the C_{W_p} to speed up, much like a high CD gain.

WVS technique was intended to be used with virtual panels which are potentially larger than physically available. However, in our second study, we use the technique when the virtual panel has the same size as a physical touchscreen. Moreover, we shifted the warped origin W_O, which slightly changed the y coordinate range but provide no other differences to the technique. We did it because the center of the one-handed smartphone input is the center of a thumb zone, which is located below the center of a touchscreen.

Our implementation of the VWS technique is intended to test the efficiency of the technique to provide easier access to the targets on the edges or outside of the thumb-zones of a touchscreen. The technique was tested with one-handed finger input for the first time as well. As we use only part of the touchscreen, which is comparable with the size of the smartwatches, the results may also indicate the applicability of VWS to wearable devices with a touchscreen.

Chapter 4: User Study 1 – Direct vs. Indirect Input Performance

We conducted a Fitts' law experiment comparing two virtual smartphone screen positions in VR. Our objective was to determine which condition offered better user performance and would be preferred by participants. Also, we wanted to determine if it is necessary to have 6DOF tracking of the VR smartphone screen (the real world-like Direct condition) for comfortable smartphone usage in VR. The study was conducted remotely without any physical contact with the participants.

4.1 Hypothesis

Past studies mostly revealed only small and non-significant differences in selection performance between Direct and Indirect input conditions [28,76]. This may indicate that any performance difference is lower than the measurement error. However, this may not be the case for smartphone usage in VR, especially for "cardboard" VR. We note that our implementation (see Chapter 3) for both SVR rotation tracking and SHI motion tracking is imperfect, and likely less performant than commercial tracking systems. Tracking delays, despite being minimized, still may overcome the advantage of the more natural Direct interaction. We also note that spatial input rotation to vertically oriented screens became quite common with the spread of personal computers and their mouse/keyboard input. Therefore, we do not expect the Indirect input condition to have a great impact on performance.

We expect Throughput to provide the key insights in this user study. It has been shown to be constant regardless of participants' bias towards speed or accuracy and thus considered a more consistent metric [23,56]. Moreover, it should not be affected by the resolution and screen size differences of the different smartphones used in the user study.

Different screen sizes may have a slight influence on the target amplitudes and widths, but the influence would be the same on both parameters, which won't change throughput according to Equation 1 and Equation 2. Therefore, we consider Throughput as a primary dependent variable of this study.

Overall, while we expect the Indirect condition to offer better results in subjective questionnaire answers, we do not expect to detect a significant difference in performance. Moreover, we hypothesize that conditions will be statistically equivalent in terms of performance.

4.2 Participants

We recruited 12 participants (6 males, 6 females, aged from 19 to 49, μ = 30.33, σ = 10.32). One participant was left-handed. In terms of VR experience, 58.3% reported having no VR experience, 41.7% reported several times a year. Participants were recruited from university students and acquaintances of the authors via invitation emails. Participants did not receive compensation to participate in the study but were provided with a VR Shinecon head-mounted display to keep (valued at $15 CAD).

4.3 Apparatus

Each participant required two smartphones for this study, one SVR device (i.e., the smartphone acting as a VR display), and one SHI device (i.e., the smartphone for hand input). We provided each participant with a smartphone-based VR headset "VR Shinecon Box 3D model DV626-9686f" (see Figure 3) to house their SVR device. These devices were ordered online and shipped directly to participants to avoid direct contact during the COVID-19 pandemic. Since the study was conducted completely remote each participant used a different pair of smartphones as apparatus in the study. We recorded the smartphones used for both the SVR and SHI devices for each participant. These are summarized in Table 2.

Participant ID	SVR Device	SHI Device
1	Samsung Galaxy S10	Sony Xperia X
2	Samsung Galaxy S10	Sony Xperia X
3	Nexus 6P	Lenovo K5 Pro
4	Nexus 6P	Lenovo K5 Pro
5	Samsung Galaxy S20 Ultra	Samsung Galaxy J8
6	Samsung Galaxy S20 Ultra	Samsung Galaxy J8
7	Nexus 6P	Samsung Galaxy S10e
8	Nexus 6P	Redmi Note 8 Pro
9	Samsung Galaxy S7	POCO F1
10	Samsung Galaxy S7	POCO F1
11	Samsung Galaxy A6	Xiaomi Mi 10 T Pro
12	Samsung Galaxy A6	Xiaomi Mi 10 T Pro

Table 2: List of smartphone models used by participants as SVR and SHI in User Study 1.

Finally, participants used chairs or armchairs with armrests to reduce physical strain during the study. Figure 11 depicts a typical setup, required to participate in the study.

Figure 11: Typical setup for the study: a) Chair with armrests; b) Smartphone-based VR headset (provided to participants); c) Two Android OS smartphones.

During the study, the SVR device was placed inside the VR headset, used as HMD, and used the integrated back-facing camera to track the SHI device. The virtual model of a smartphone showed in a VR environment at the tracked SHI position. SHI screen feed is also translated to VR environment and rendered in Direct or Indirect mode. Meanwhile, SHI was running the Fitts' law task, recording the participant selection performance data, sending the screen feed to SVR, and rendering a fiducial marker at the upper part of the screen. The VR and real-world first-person view of the system can be found in Figure 12. A detailed description of the used software is seen in section 3.2.

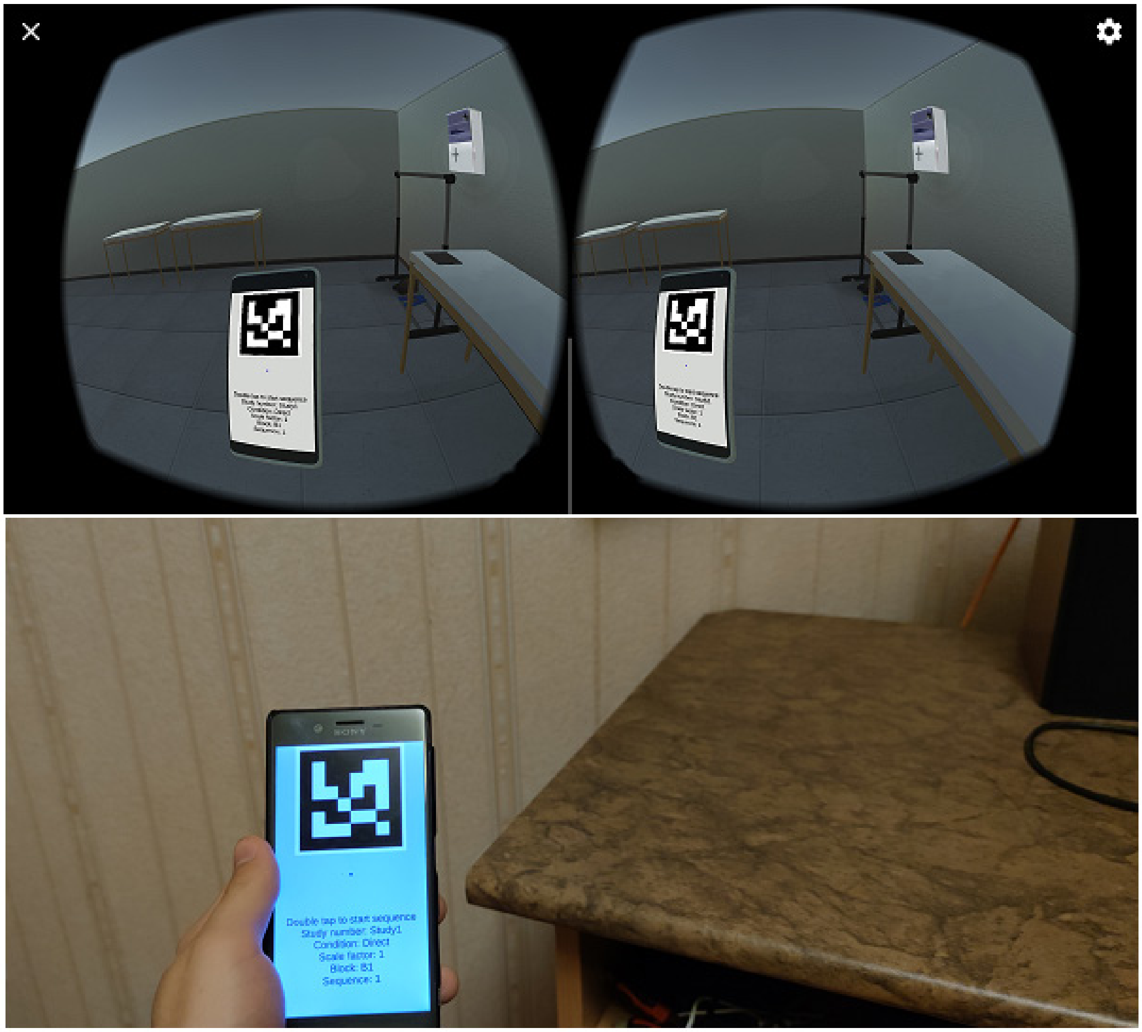

Figure 12: VR vs. real-world first-person view: upper image shows the VR environment view (user's view) and at the bottom is the same view in the real world.

4.4 Procedure

In an effort to minimize person-to-person contact during the COVID-19 pandemic, the experiment was conducted fully remotely, and we sent the VR headsets to participants via mail. Before starting the study, participants completed the consent form (Appendix A) and completed a demographic questionnaire (Appendix C). We provided all the documents such as the consent form, instructions (Appendix B), and questionnaires in an online format. The instructions included information on how to set up and use the software on smartphones and a description of actions expected from a participant during the study. We also used video calls with the participants during the study to provide extra assistance and answer any questions during the study. Figure 13 depicts a participant during the study.

Figure 13: A participant during the pilot study with a smartphone aligned with the virtual screen in VR.

The study consisted of 2 conditions across 6 blocks, i.e., 3 blocks for each condition. Each block consisted of 10 sequences, one for each of the 10 indices of difficulty (IDs). Each sequence consisted of 15 trials, where each trial required selecting one target. The task involved selecting circular targets, placed in a circle, as typical in Fitts' law-based experiments (see Figure 14). Participants were instructed to select the targets as quickly and as accurately as possible. Each sequence started by a double-tap on the SHI smartphone screen. The system tracked the participants' finger position only when their fingers touched the screen. Participants thus had to hold their fingers pressed to the screen at all times during a sequence. The target was considered selected when the cursor's center was placed inside the target circle's border. The timer for the sequence started with the selection of the first target. Targets that were not selected within 10 seconds were considered errors. Regardless if a target was hit or missed (or timed out), the next target in the sequence was then activated.

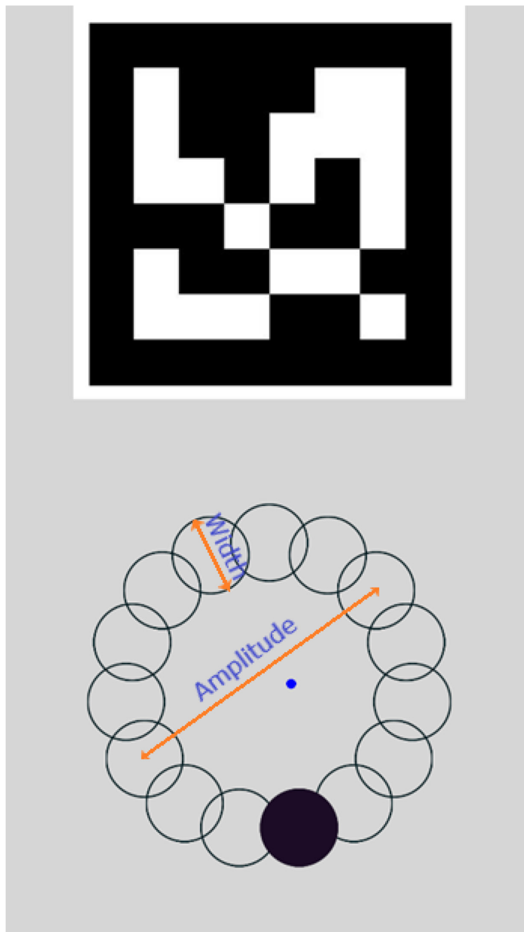

Figure 14: Fitts' law selection task in FittsStudy app.

Prior to starting the study, participants did 3 practice sequences with the Direct condition for training. These practice trials were not recorded. Participants could rest between sequences and after each block, as the timer stopped at these points. During these breaks, they could remove the HMD as desired. After completing the first half of the study (i.e., 3 blocks) the condition changed. At that point, the participant was asked to remove the HMD and answer some questions about the condition they had just finished. In total, the experiment took about 60 minutes, with participants using VR for ~35 to 45 minutes.

After completing the second condition and answering the corresponding questions, participants filled out a device assessment questionnaire and gave comments on their experience using a smartphone in a VR prototype. They were then debriefed (via video call) and reminded to keep the VR headset as compensation for their participation.

4.5 Experiment Design

Our study used a within-subjects design with two independent variables: Input Condition and Index of Difficulty (ID). The Direct and Indirect conditions are described fully in section 3.2.1.1.

Input Condition: Direct, Indirect;

ID: 1.1, 1.3, 1.5, 1.8, 2.1, 2.4, 2.7, 3.0, 3.3, 3.6

The ID values were calculated according to Equation 1 from the following 10 combinations of amplitude and width (in pixels):

ID	**1.1**	**1.3**	**1.5**	**1.8**	**2.1**	**2.4**	**2.7**	**3.0**	**3.3**	**3.6**
A	115	145	295	400	265	345	220	350	440	445
W	100	100	160	160	80	80	40	50	50	40

Table 3: Index of Difficulties with their corresponding Amplitudes and Widths.

To counterbalance condition order, half of the participants did the Direct input condition first, while the other half started with Indirect. The study contained 6 blocks, 3 for each condition. Within each block, the ID ordering was randomized, with one ID per sequence of 15 targets. Each participant completed 6 blocks × 10 IDs × 15 targets = 900 selections in total. Across all 12 participants, this yielded 10800 target selections in total.

Our experiment's dependent variables included:

- **Throughput:** calculated according to the ISO 9241-9 standard and based on Equation 2, in bits per second (bps), where a higher score is better.
- **Movement time:** the average selection time, in milliseconds, where a lower score is better.

Although Fitts' Law studies often include an error rate measure, because it was effectively impossible to miss the target in our study, we excluded the error rate variable.

4.6 Results

For Throughput and Movement time analysis we conducted repeated-measures ANOVA (RM-ANOVA) to determine if there were significant differences between Direct and Indirect conditions. Index of Difficulty was not analyzed because it is expected to cause differences in performance. As detailed below, we did not find significant differences in Throughput and Movement time.

To test our hypothesis – that there was no difference in Direct vs. Indirect input – we employ equivalence testing since standard statistical ANOVA tests do not determine equivalence, only differences. In other words, a non-significant ANOVA result does not indicate two conditions are equivalent. Thus, for non-significant ANOVA results, we also conducted equivalence testing for Throughput. We used the same indifference zone (1 bps) as previous studies [22,45]. We did not conduct the equivalence testing for Movement time, because it is unclear what indifference zone to use [45].

4.6.1 Throughput

Mauchly's test did not reveal a violation of sphericity in TP data, thus we employed a common RM-ANOVA test ($\alpha = .05$). RM-ANOVA on Throughput revealed no significant difference for condition ($F_{1,11} = 0.29, ns$). The mean TP difference was 0.0297 bps. See Figure 15.

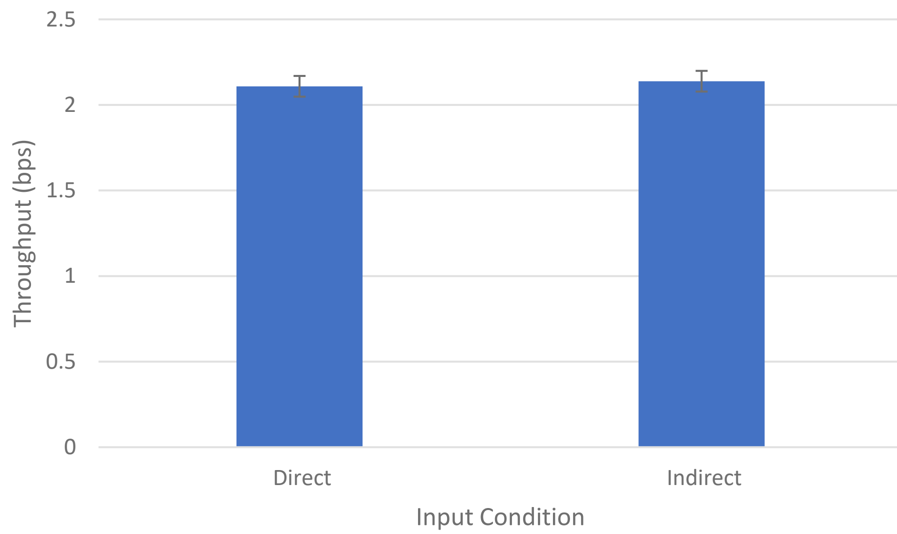

Figure 15: Mean TP for each condition. Error bars indicate 95% CI.

To determine if throughput was statistically the same between Direct and Indirect input, we conducted our equivalence test ($\alpha = .05, \delta = 1\ bps$, see Section 2.5). With the indifference zone of 1 bps, the mean difference between compared condition and the bounds of the two-tailed confidence intervals should be lower than 1 bps to be considered equivalent. Table 4 shows the results of the equivalence test between the conditions.

Pair	**Mean Diff.**	**Direct 2-tailed 90% conf. Interval**	**Indirect 2-tailed 90% conf. Interval**	**p1**	**p2**
Direct-Indirect	0.0297	-0.199 +0.560	-0.401 +0.321	< 0.0001	< 0.0001

Table 4: Mean TP differences and equivalence test results.

Based on this analysis, the Direct and Indirect conditions were considered equivalent on Throughput (i.e., they have statistically the same TP). Overall, this result indicates that throughput is not affected by virtual screen position, in line with our hypothesis, and is consistent with past results on decoupling control/display spaces [27,28,45,76].

4.6.2 Movement time

No violation of sphericity was revealed by Mauchly's test in MT values. Despite the Mean MT was greater than in Throughput, RM-ANOVA ($\alpha = .05$) found no significant differences between conditions in the case of movement time ($F_{1,11} = 3.18, p = 0.1, ns$). See Figure 16. Despite this non-significant difference, we did not conduct the equivalence test for movement time, because, as suggested by Kohli et al. [45], it is not clear what indifference zone for movement time would be reasonable.

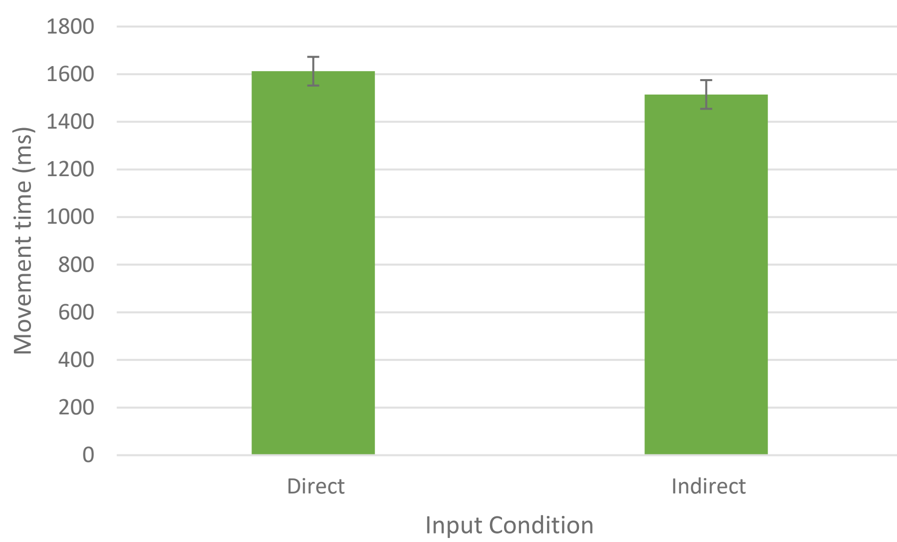

Figure 16: Mean MT for each condition. Error bars indicate 95% CI.

4.6.3 Linear Regression Analysis

We conducted a linear regression analysis to compare how the conditions fit the model and confirm the linear relation between MT and TP modeled by Fitts' law. As can be seen in Figure 17, both Input Conditions had a strong correlation as expected. However, the Indirect condition correlation ($R^2 = 0.965$) was a little better than the Direct one ($R^2 = 0.949$).

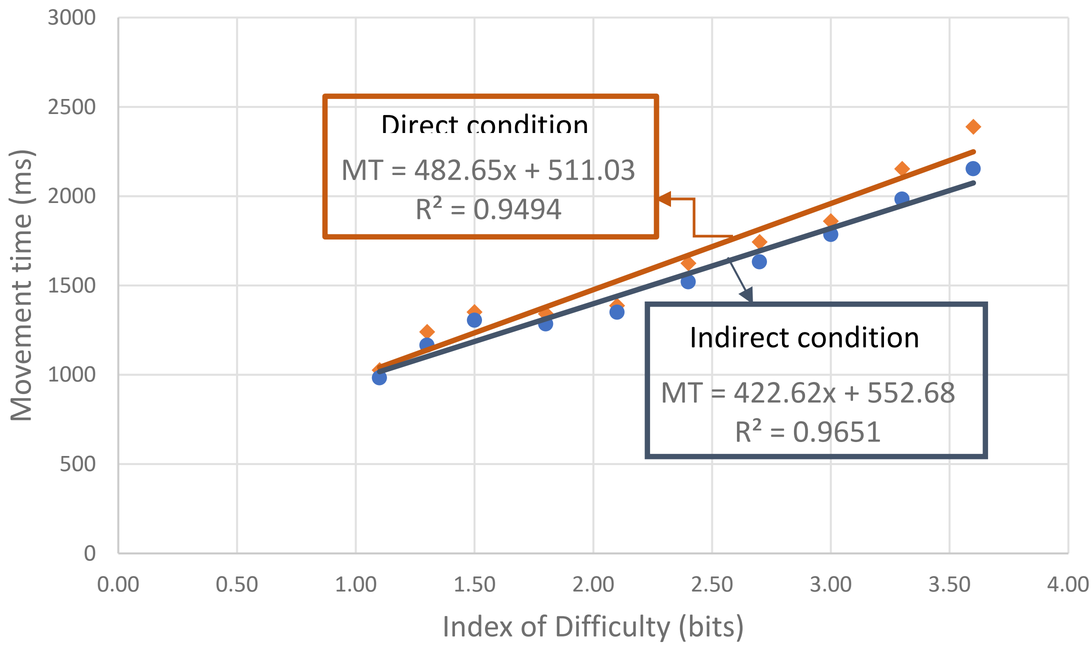

Figure 17: Linear regression of Movement time on Index of Difficulty for both conditions. Points represent average MT for all IDs across all participants.

4.6.4 Questionnaire

To indicate a subjective preference between conditions we asked participants 4 questions:

1. Physical effort required (from very low to very high).
2. The fast selection was (from very easy to very hard).
3. The accurate selection was (from very easy to very hard).
4. General comfort (from very comfortable to very uncomfortable).

We asked these questions after the corresponding condition to make a comparison. Participants rated each question from 1 (lowest) to 5 (highest). We conducted the Friedman non-parametric statistical test ($\alpha = .05$) but did not find any significant differences between conditions in participants' answers. The assessment results are seen in Figure 18.

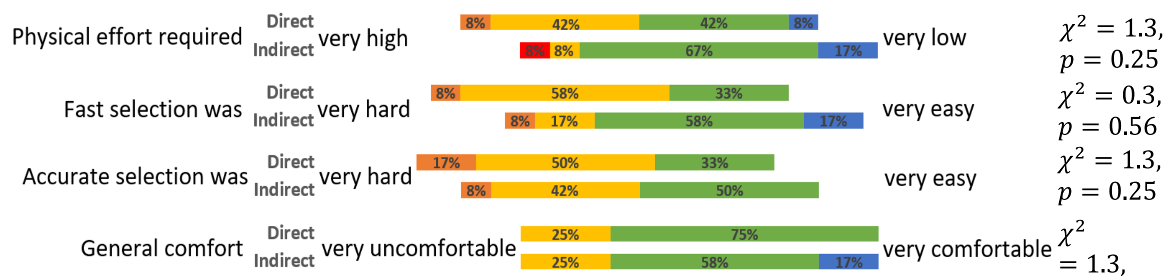

Figure 18: Subjective preference assessment. Colors are red, orange, yellow, green, and blue from negative to positive answers and the numbers are percentages of participants answered.

We also used the device assessment questionnaire provided by *ISO 9241-9* [23] to evaluate fatigue, accuracy, and the overall experience of using finger input with a smartphone in VR. Results are summarized in Figure 19.

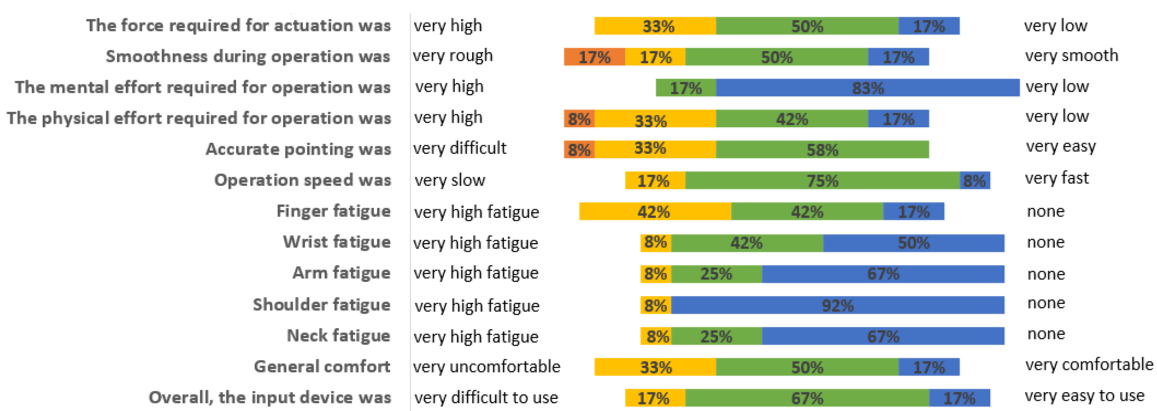

Figure 19: Device Assessment Questionnaire. Colors are red, orange, yellow, green, and blue from negative to positive answers and the numbers are percentages of participants answered.

4.7 Discussion

Results indicate that virtual screen position (Direct and Indirect variants) has no significant effects on TP and MT. Equivalence testing showed that Throughput is the same for the Direct and Indirect conditions.

The most important result of the study is that there are no significant differences in selection performance due to virtual screen position. This suggests that when using a smartphone in VR, the Direct (i.e., real world-like co-located smartphone) condition is not necessary. This may be quite important for VR solutions, where tracking methods have high power and processing time requirements; if Indirect input works as well as Direct input, then such tracking may be unnecessary. For example, when using Cardboard VR, camera-based tracking requires that the camera was always activated, which greatly increases battery drain and smartphone temperature. During our study, 4 participants had their smartphones overheat and needed a 5-minute break to wait until the smartphone cooled down to finish the study. With Indirect input, it is possible to use the tracking only when the user needs to pick up the smartphone, and tracking can be disabled when the user is otherwise touching the screen.

Participants gave us some verbal feedback about conditions during the study. While most of the participants were excited about the tracking method used in the study, half of them said that it was sometimes a little harder to see the contents of the virtual screen due to the imperfectness of the tracking (e.g., small drifting of the virtual screen). Some participants noted, that the Indirect condition is better for long usage because you don’t need to have your head always lowered or hand always held up to see the screen. One participant noted that the Indirect condition is less natural or realistic than the Direct one. While both options likely reduce the level of immersion and sense of presence, if the input smartphone is part of the realistic game (as a game object or prop), the Direct condition may be preferable.

Most participants gave comments like “the small circles are much harder to select, I like the big ones”. Some participants needed to slightly change their grip of the smartphone to select targets during the highest ID sequence, which was on the edge of their thumb zones. Some participants tried to help themselves to hold the device with the other hand. To keep the study consistent (all participants made a one-handed input and smartphone grip), we asked them to reposition their hand with a smartphone to a more comfortable position instead. After the study, 3 participants (who were familiar with current VR technologies, like Oculus Quest) said, that it would be a nice feature to be able to use a smartphone during a VR session.

Finally, we found some insights, which may be helpful to conduct similar remote studies in the future. Despite the previous pilot testing, some participants needed twice the experiment setup time than the others, which caused the experiment to run longer than expected. For future similar studies, we suggest giving more time for setup installment or even doing it in a separate session before the study for hard setup cases. Although most participants liked the remote study idea in general, some participants gave comments and suggestions about the remote studies. One participant suggested the idea to create some unified platform for similar research, which may contain the options to select the studies you want to participate in, have a way to communicate with the researcher during the study, and gather feedback from participants. Four participants noted that, while smartphone-based HMD was fine, monetary compensation would be preferable.

4.7.1 Limitations

The main limitation of the study is the usage of a "cardboard" VR device. Although the results give insights about the usage of smartphones in VR with other VR headsets, we do not know for sure if our results would transfer to other HMDs. Due to VR cardboard usage, we had to use a smartphone camera to track the second smartphone, which allowed much worse tracking quality than infrared cameras or multiple monochromic cameras such as HTC Vive and Oculus Quest have.

Another limitation is the lack of 6DOF finger tracking (although other VR solutions do not support it yet as well). The study was conducted without any physical contact with participants. Therefore, while all the participants used the same VR HMD sent to them, the smartphone device models used in the study were mostly different. This introduces some possibility of confounding variables due to different equipment differences. Conversely, this also enhances the external validity of our experiment, as the results generalize to a wider range of hardware.

Another issue, as mentioned by Didehkhorshid et al. [22], is throughput indifference zones for equivalence testing, although the same as previous studies [22,45] are still up for debate. Choosing a different indifference zone value could alter the results (i.e., whether conditions were deemed "the same" or not). Finally, we did not ask participants to fill separate device assessment questionnaires for both conditions, because it was not the main goal of our study and to keep the experiment under an hour. We believe our findings can still be useful and can help VR researchers and system designers.

4.8 Conclusion

In this study, we introduced the technique to use a smartphone in VR with screen streaming and 6DOF smartphone tracking. We evaluated the effects of virtual screen position on selection task performance with one-handed finger input using a smartphone in VR. In terms of TP and MT, we did not find any statistical differences between the conditions. The equivalence statistical test showed that Throughput was statistically the same between the conditions.

In the next chapter, we present a study, in which we modify smartphone input even further, by adding input surface warping. While this makes the system even less natural, it also increases the size of the thumb zone facilitates simulation of interaction with larger virtual surfaces. In the next study, we seek the answer to the important question: does such surface warping significantly reduce user performance?

Chapter 5: User Study 2 – Effects of Surface Warping on Performance

Our previous study established that decoupling the interaction plane from the physical location of a smartphone in VR had little impact on user performance. Taking this idea further, we conducted a second Fitts' law experiment comparing several cursor scale factors. Employing scale factors (similar to mouse CD gain) allows us to further decouple the cursor from the actual finger position; in other words, the virtual smartphone surface in VR can be potentially larger, allowing a small tactile surface to act as a proxy for a larger virtual object in VR. Our study also included a Scale Factor equal to 1 (i.e., a 1-to-1 mapping between the finger position and cursor position). We had two objectives. The first was to determine if the warped virtual surface (WVS) technique [22] can make one-handed finger input using smartphones in VR easier. Second, previous studies used the WVS technique with stylus input using a tracked tablet in VR and found that warped (i.e., scaled) conditions were statistically equivalent to the 1-to-1 mapping [22]. We wanted to determine if a more common one-handed finger input using a smartphone in VR would yield similar results.

5.1 Hypothesis

Previous work found no significant effects of scale factor on Throughput [22]. However, a smartphone's screen is much smaller than the tablet used in previous work, and one-handed finger input on a smartphone is different from the stylus input on a tablet. Since the distance between the targets is quite small on a smartphone screen, large SFs vastly increase the cursor movement and therefore could have a negative effect on performance.

On the other hand, when the targets are placed across the full width of the smartphone, they may be located on the edge – or outside – of the thumb zone, which means the user must fully and uncomfortably stretch their finger or awkwardly change their grip on the smartphone. Moderate surface warping may effectively put far-located targets in the thumb-zone, while still being comfortable for short-distance targets. Therefore, small SF may even make the targets with large amplitudes easier to select and improve the users' performance.

Based on the above reasoning, we hypothesize that high scale factors (e.g., from 2.0 and higher) would yield significantly worse results compared to the 1-to-1 mapping and small SF (below 1.5). Since even the largest amplitudes of our targets should be inside the smartphones' thumb-zones, we do not expect the small SF to be significantly better than 1-to-1 mapping.

5.2 Participants

We recruited 12 participants (5 females, aged 18 to 50, $\mu = 26, \sigma = 8.16$). Two of them were left-handed. We asked about their VR experience and found that 41.7% had never used VR, 50% used VR several times a year, and 8.3% experienced VR several times a month. Eight out of twelve participants previously took part in User Study 1 (see Chapter 4).

5.3 Apparatus

The study was conducted with almost the same apparatus as described in the previous study (see Section 4.3) and used the same software as described in section 3.2. The difference from the previous study was only in smartphones used by participants (although most of the participants were the same and used their devices again). See the SVR and SHI devices employed in Table 5.

Participant ID	SVR Device	SHI Device
1	Samsung Galaxy S10	Sony Xperia X
2	Samsung Galaxy S20 Ultra	Sony Xperia X
3	Nexus 6P	Lenovo K5 Pro
4	Nexus 6P	Redmi Note 7
5	Samsung Galaxy S7	POCO F1
6	Samsung Galaxy S7	POCO F1
7	Redmi Note 9	Redmi Note 8 Pro
8	Redmi Note 9	Redmi Note 8 Pro
9	Samsung Galaxy S8	Samsung Galaxy S20
10	Samsung Galaxy S8	Samsung Galaxy S20
11	Samsung Galaxy A6	Xiaomi Mi 10 T Pro
12	Samsung Galaxy A6	Xiaomi Mi 10 T Pro

Table 5: List of smartphone models used by participants as SVR and SHI in User Study 2.

Given there was no difference in performance but slight user preference for Indirect, we decided to always use the Indirect screen condition for this study. Like in the preceding study, the virtual smartphone model was still tracked to show smartphone position in VR with a black screen. A complete description of the Indirect condition can be found in section 3.2.1.1.

5.4 Procedure

Similar to the previous experiment, this experiment was conducted remotely due to the COVID-19 pandemic. Again, we sent the VR cardboard headsets to the participants and asked them to use their own mobile devices. Similar to the first study, all the instructions (Appendix B), questionnaires (Appendix C), and the consent form (Appendix A) were provided to participants in an online format. We again used real-time video calls with the participants during study sessions for extra support.

Participants conducted the same selection task described in section 4.4. Participants selected targets as quickly and accurately as possible, by moving their finger on the smartphone touchscreen to move the cursor displayed on the virtual smartphone screen. Unlike the first experiment, this study included 8 different scale factors, and participants completed one block for each scale factor. Each block consisted of 8 sequences, one for each of the 8 IDs. Each sequence required 15 target selections. The experiment took about 60 minutes, with participants selecting targets in VR for ~45 to 50 minutes.

Before starting the study, participants provided informed consent and completed a demographic questionnaire. Next, participants had 3 practice sequences with the 1-to-1 mapping. These practice trials were not recorded. Participants were able to rest between each sequence and after each block and could remove the HMD during these breaks.

After completing all selection trials, participants answered the question (from 1 to 5 score): "How, in your opinion, did the different scale factors influenced your performance?". Then participants filled out the ISO 9241-9 device assessment questionnaire and gave comments on their experience in the study. They were then debriefed and reminded to keep the VR cardboard headset as compensation for participation.

5.5 Experiment Design

The study employed a within-subjects design with two independent variables: Scale Factor and Index of Difficulty (ID).

Scale Factor (SF): 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4;

ID: 1.1, 1.5, 1.8, 2.2, 2.5, 2.9, 3.2, 3.6

The SFs were counterbalanced according to a balanced Latin square. Due to the impossibility to fully counterbalance 8 conditions over 12 participants, participants from 9 to 12 had the same order as participants from 1 to 4.

The ID values were calculated according to Equation 1 from the following 8 combinations of amplitude and width (in pixels):

ID	**1.1**	**1.5**	**1.8**	**2.2**	**2.5**	**2.9**	**3.2**	**3.6**
A	115	295	400	290	375	325	410	445
W	100	160	160	80	80	50	50	40

Table 6: Index of Difficulties with their corresponding Amplitudes and Widths.

The SFs were applied to the cursor position using the WVS technique as described in section 3.4. The study contained 8 blocks in total, one SF per block. The order of SFs was counterbalanced according to a balanced Latin square. Within each block, the ID order was randomized, with one ID per sequence of 15 targets. In total, there were 8 blocks × 8 IDs × 15 targets = 960 selections in total. Multiplied by the 12 participants which took part, this yields 11520 target selections in total.

Our dependent variables included:

- **Throughput:** calculated according to the ISO 9241-9 standard and based on Equation 2, in bits per second (bps).
- **Movement time:** the average selection time, in milliseconds.

- **Rotation:** the sum of SHI rotation angle during the task sequences execution (tracked via SHI gyroscope data). To get this sum we added absolute values of the angle between tracked SHI rotations each 10ms.

Similar to our first study, because of the finger tracking with a touchscreen in VR specialty, the error rate variable was excluded from recording since it was effectively impossible to miss the target. The Rotation dependent variable gives an indication of how much the user shifts SHI during the study. Users may shift the smartphone or change their grip on it more if the targets are at the edge of the thumb zone or they are just hard to hit. Much like the first study, we expect Throughput to provide the key insights in this user study.

5.6 Results

Similar to our previous study, we conducted the RM-ANOVA test to find a significant main effect and Bonferroni adjustments. This time, however, we had 8 different values of our independent variable Scale Factor. Unlike in a similar study with a virtual stylus [22], we found significant differences between scale factors, Horizontal bars (●·····●) in Figures Figure 20 and Figure 21 indicate pairwise significant differences between scale factors based on Bonferroni adjustments.

5.6.1 Throughput

Mauchly's test did not reveal a violation of sphericity, thus we employed a common RM-ANOVA test ($\alpha = .05$). RM-ANOVA on Throughput revealed a significant difference for scale factor ($F_{7,77} = 8.05, p < 0.001$). Mean TP values and posthoc pairwise differences test results are seen in Figure 20. Results indicate that larger SF values yielded lower mean Throughput, which means that participants were more effective with lower SFs. Our hypothesis was confirmed in the case of Throughput.

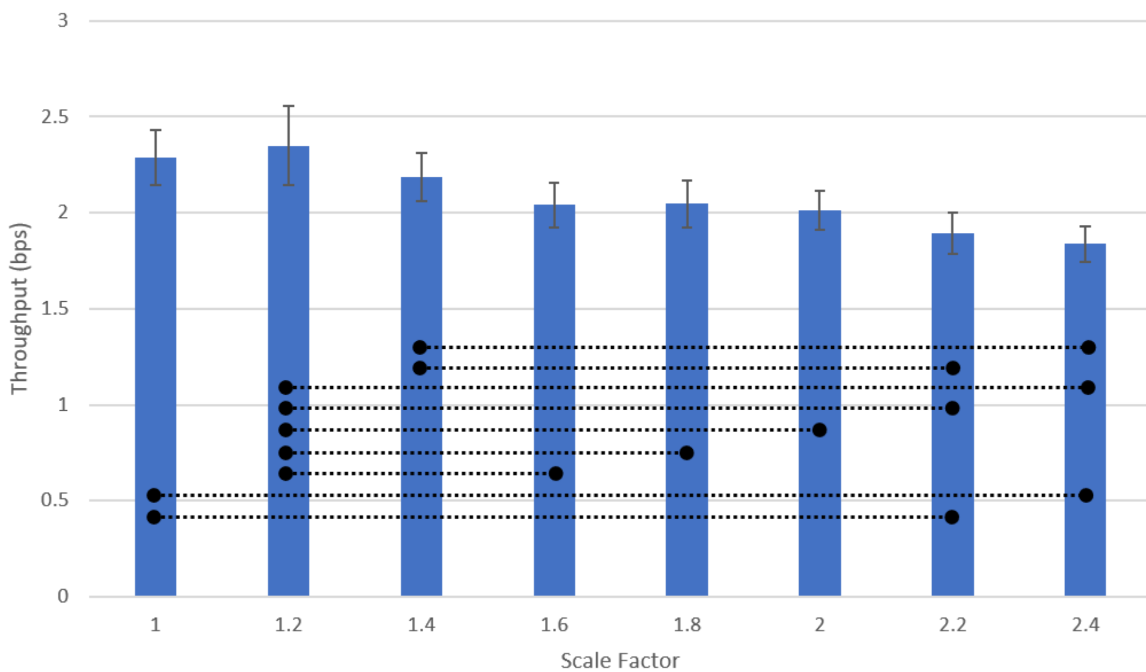

Figure 20: Mean TP for each SF value and their pairwise significant differences. Error bars indicate 95% CI.

5.6.2 Movement time

RM-ANOVA revealed significant differences for movement time as well ($\alpha = .05$). No violation of sphericity was revealed by Mauchly's test. There was a significant main effect of Scale Factor on Movement time ($F_{7,77} = 3.81, p = 0.001$). Post-hoc pairwise differences and mean MT scores are seen in Figure 21. Results indicate that over 2.0 SF values caused the participants to select targets slower, which confirms our hypothesis.

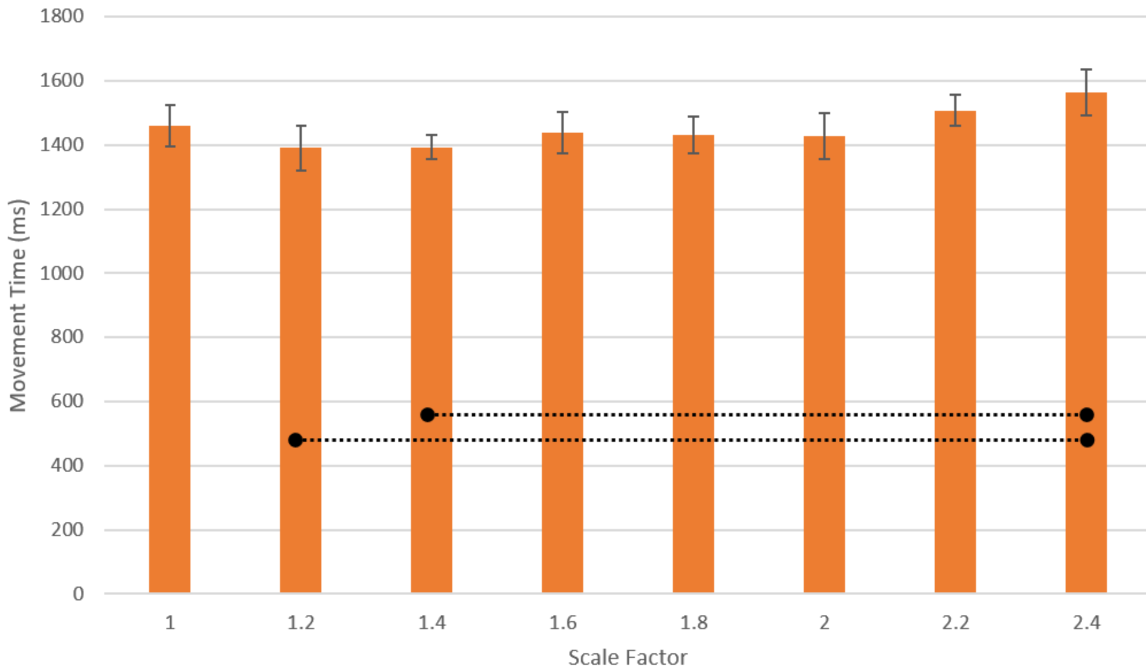

Figure 21: Mean MT for each SF value and their pairwise significant differences. Error bars indicate 95% CI.

5.6.3 Rotation

As seen in Figure 22 error bars, there was a great degree of variability in the total rotation sums. This is likely due to the varying error level of gyroscopes and differences of the sensors across used the smartphones used in the study. Mauchly's test revealed that the assumption of sphericity was violated ($\chi^2(27) = 198.3, p < 0.001$) so we applied Greenhouse-Geisser correction ($\varepsilon = 0.27$). The effect of scale factor on Rotation was not significant ($\alpha = .05, F_{7,77} = 0.18, p = 0.82$).

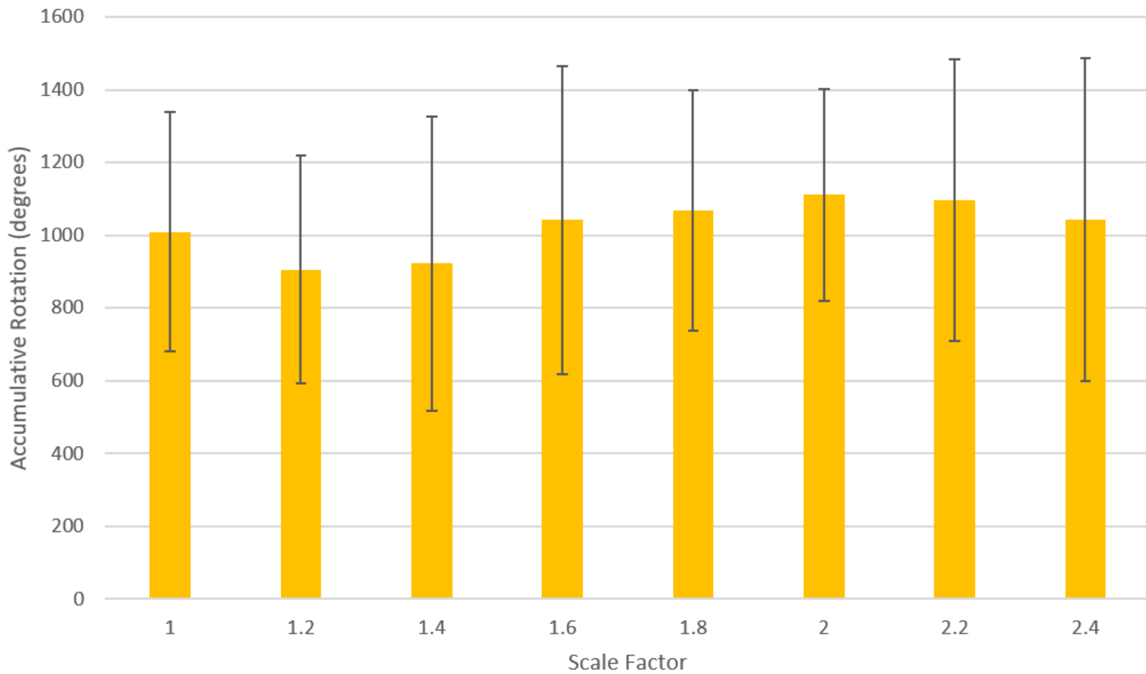

Figure 22: Mean Rotation for each SF value. Error bars indicate 95% CI.

5.6.4 Linear Regression Analysis

As Fitt's law implies a linear relation between MT and TP, we conducted a linear regression analysis to confirm it for our study. Figure 23 depicts the regression model with average MT for each SF and ID combination. As expected, the MT and ID relation strongly fit the linear model ($R^2 = 0.94$).

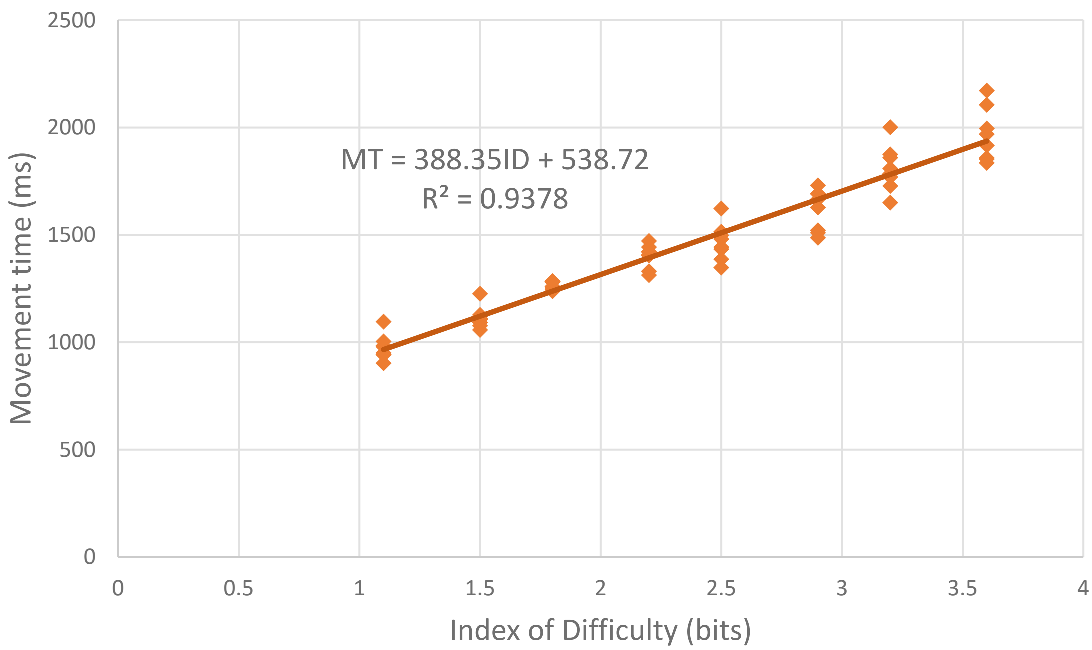

Figure 23: Linear regression of Movement time on Index of Difficulty. Points represent average MT for all SF and ID combinations across all participants.

5.6.5 Questionnaire

Figure 24 shows the subjective opinions of participants about the SF influence on selection performance. Overall, while answers were distributed from low to high, participants believed that SF influenced their performance (which was confirmed by significant results on TP and MT).

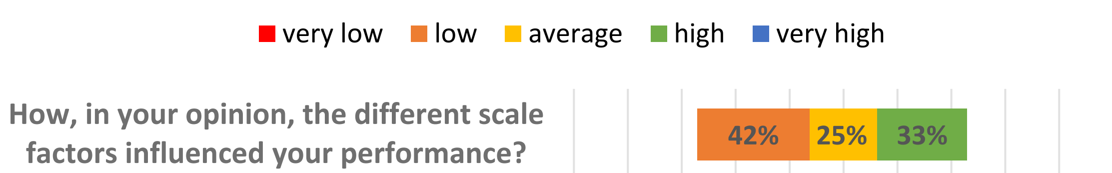

Figure 24: Distribution of subjective opinions about the influence of scale factors on selection performance.

Finally, we conducted Device Assessment Questionnaire (see in Figure 25). Compared to participants' responses in the first study (see in section 4.6.4) the accurate pointing answers are more skewed towards "very difficult" likely due to surface warping with high SF.

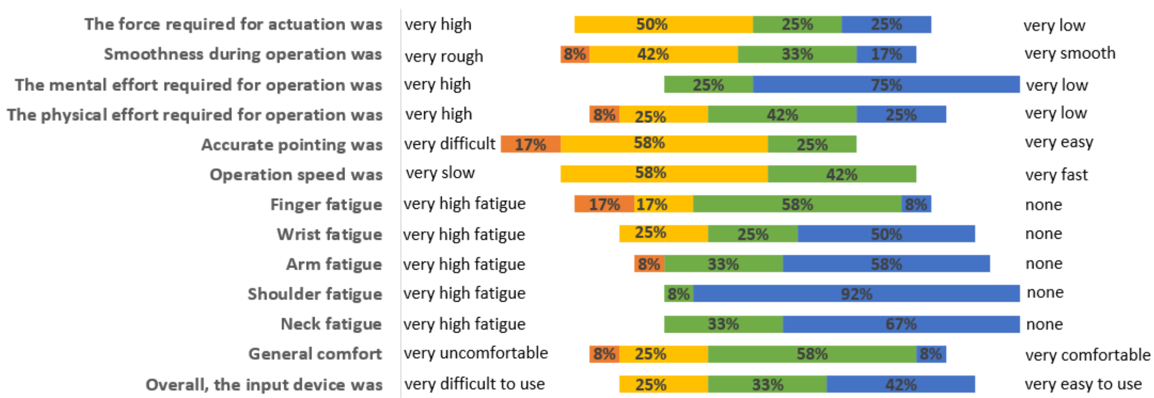

Figure 25: Device Assessment Questionnaire. Colors are red, orange, yellow, green, and blue from negative to positive answers and the numbers are percentages of participants answered.

5.7 Discussion

Results indicate that the WVS technique with smartphone finger input in VR had significant effects both on Throughput and Movement time. The small SFs (below 1.5) were significantly better than large SFs (1.6 and above).

Unlike the past work with stylus and tablet input in VR [22], we found significant differences caused by Scale Factor on Throughput and Movement time. This is the most important result of our study. The most probable reason for this result is the physical size difference of smartphone and tablet touchscreens. Tablets are generally several times larger than smartphones. In our study smartphones were held with a vertical orientation in one hand and input with the same hand's finger, which made the actual interactive zone even smaller. At the same time, we used the same SFs as was used for the tablet in the previous study. As a result, unlike the previous study using a tablet [22], we found the maximum SF which can be applied to smartphone input without significant influence on performance and it appeared to be roughly 2.0. Such results are quite important for the following reason. While further research is required to confirm it, our results indicate that users with 2.0 SF plane warping would be able to cover twice the size of the thumb-zone with only a small (but significant) drop in the efficiency. Even for a huge smartphone (e.g., "phablets" around 6 inches) the thumb-zone usually covers at least half of the screen. The plane warping may help the user to comfortably work with UI all over the smartphone screen area during one-hand input via thumb.

Notably, the 1.2 SF condition was not only significantly better than 2.2 and 2.4 but also better than 1.6 and 1.8. The condition was even slightly, though not significantly, better than 1-to-1. This may indicate that a small SF can help to select objects at the edges of the screen even without notice from users.

While all the participants noticed some changes in input during high SF, some of them were not able to explain what was different without a hint. Two participants said the small SF helped them to reach the targets on the edge of the smartphone. They said: "During some conditions, I dragged my finger on smaller distances to hit the targets, so I didn't need to struggle and stretch my thumb to select the ones that were far away, it was helpful".

Most of the participants were the same as in our previous study, thus they had a general idea of what to do and even had the software installed. The time constraints were tight, more than in study 1, therefore this was quite helpful. Another thing we noticed during the study is that people who were more familiar with the Android apps usage were faster with the setup process than others. Therefore, for future remote studies, we recommend asking people about their familiarity with the Android apps usage and plan the time allocation accordingly.

We kept the virtual smartphone model tracking enabled to have a similar CPU/GPU load on a device during both studies. However, some participants said that the movement of a virtual model behind the screen distracted them from the task. A possible improvement for future work is to disable smartphone tracking and rendering when the smartphone is already in hand and dim the virtual environment during the possible smartphone usage during the pause in a real VR game/application.

5.7.1 Limitations

Most of the same limitations of the first study also apply here (see section 4.7.1). The limitation about different mobile devices used by participants influenced this study more. This is the main reason the Rotation dependent variable was highly variable.

The circle with targets was at the bottom of the screen and in a thumb-zone of the participants. We placed the warped origin position at the center of the circle of targets. We have not studied the WVS technique performance in selection targets which fully outside of a real thumb zone, which should be done to fully confirm the possibility to use WVS to increase one-handed touchscreen coverage. In such a case, the center zero-warping point may be placed differently from the position chosen by us (e.g., place it a little lower the center of the thumb zone to increase the covered area to the upper bound of the screen). However, we believe our results have partly covered the smartphone in VR usage and can be helpful to the smartphone/VR designers and developers as well as smartphone and VR researchers in future studies.

5.8 Conclusion

In this study, we employed the WVS technique with a smartphone in VR with the screen positioned in front of the user. We evaluated the effects of different surface warping scale factors on selection performance in terms of throughput, movement time, and accumulative rotation.

We found a significant main effect of scale factors on throughput and movement time. Our results indicate that, while small surface warping may make the one-handed selection of far located objects easier, scale factors 2.2 and higher have a negative influence on user performance.

Chapter 6: Conclusions

Our prototype and user studies have shown that a smartphone can be integrated and used in VR, even with a low-cost VR headset such as Cardboard HMD. We compared co-located and disjoint virtual screen conditions. Equivalence testing showed that performance in the disjoint condition was the same as in the co-located one. This means that constant 6DOF tracking of the smartphone is not required for comfortable smartphone usage in VR. It still may be beneficial to locate the device before taking it in the hand.

To further explore the design space of smartphone-based interaction in VR, we also looked at the possibility of using input redirection via the WVS technique. The rationale for including this was to determine the extent to which a smartphone can be repurposed as a larger virtual tactile surface in VR, by scaling the interaction space. Our results indicate that there are limits to how much scaling is possible before user performance is affected. While the selection task results were not significantly different for scale factors below 2.2, for scale factors of 2.2 and higher, both throughput and movement time were significantly worse. From this, we conclude that the WVS technique can be used to some extent to increase the effective touchscreen area for selection tasks. And, since practically all apps usage in a smartphone consists of sequences of selection tasks, this conclusion probably extends to basic app usage.

Based on our results, we recommend co-locating the virtual screen with the physical smartphone, if phone interaction realism is required and device performance is not an issue. Otherwise, our results suggest that the disjoint solution may be a good option since it offers statistically the same performance in terms of throughput and movement time (see Figure 15, Figure 16). The disjoint screen can also optionally be combined with tracking at the start of an interaction, to initially assist in locating the tracked phone while wearing a head-mounted display that occludes the outside environment. As for scale factors, we recommend using a modest scaling (up to 2.0), since they seem to only have minimal impact on user performance (see Figure 20, Figure 21).

6.1 Smartphone in VR applications

Our technique would enable a smartphone to be integrated into VR using modern camera-based headsets, such as Oculus Quest. The possibility to answer a call or chat message without removing the VR headset would likely increase engagement with VR applications, and avoid breaks in presence or workflow. Unfortunately, Facebook's Oculus SDK currently does not provide access to the Oculus Quest camera feed; thus, it is not currently an option to implement our approach on such devices as a third-party application. However, it would be a useful optional feature to have off-the-shelf. The same is true for other VR headsets, but of course, a different tracking method will be necessary for headsets.

Our approach also would allow smartphones to be integrated into specific VR apps to use as a VR controller. The user could take advantage of a touchscreen for more accurate VR interaction with haptic feedback without the need to buy any extra devices. Likewise, the smartphone in VR integration can be employed in common VR gaming as well as in VR design sessions and immersive workflows.

6.2 Conducting Remote Experiments Challenges

Running an experiment requiring specialized hardware fully remotely was quite challenging. The COVID-19 pandemic made the process much more difficult due to safety reasons. In this subsection, we summarize the experience of conducting remote studies during the global pandemic.

We decided to stick with only 12 participants per study mostly for two reasons. First, since it was our first time conducting the remote study, we wanted to keep the time commitment reasonable, in case we made mistakes necessitating re-running additional participants. Second, it was difficult to find many prospective participants willing to participate who met the hardware requirements (i.e., two available Android-based smartphones). We observed such distancing protocols to guarantee the maximum safety of the participants.

In general, setting up the software and equipment for the remote study, which participants had to do by themselves, took twice as long as a similar set-up in person. Similarly, during in-person studies, a major hardware setup is usually only done once; only minor changes are made for each participant. Unfortunately, this is not the case when each participant uses their own hardware. Thus, we recommend reserving extra time for system setup, especially if the participant is not a fluent smartphone user.

Another issue was the tendency of the SVR smartphones to overheat during the study. Since the SVR devices are closed in the VR headset (trapping heat in) and the smartphone screen, camera, CPU, and Wi-Fi hotspot are always working, some devices overheated and we had to ask participants to take a rest while the smartphone was cooling down.

Other than the challenges mentioned above, we did not face any major issues in conducting the remote study. Communication with participants via Discord helped to clarify the instructions for participants, validate that the study is going smoothly, and gather verbal feedback.

6.3 Future Work

There are a lot of possible future researches that can be done in this area. First, it's important to conduct studies measuring the performance and comfort level of real smartphone usage in VR, like making calls, using messengers, making a photo, etc. It would be helpful to conduct similar experiments with other VR headsets and with tablets, smartwatches, and smartphones with different input methods (using the index finger, multi-finger input). WVS technique should be tested to be able to reach the upper side of the smartphone screen with different positions of zero-warping point (at the center of the screen, at the center of the thumb-zone). Finally, the WVS technique may be compared with other techniques which increase effective thumb-zone, such as BezelSpace [84].

Appendices

Appendix A Consent Form for User Studies

Informed Consent Form

* Required

Name and Contact Information of Researchers

Researcher:
Stanislav Kyian, School of Information Technology
stanislavkyian@cmail.carleton.ca
Supervisor:
Robert J. Teather, School of Information Technology
Rob.Teather@carleton.ca

Project Title: Selection Performance Using a Smartphone in VR with Redirected Input

Carleton University Project Clearance

Clearance #: 115464   Date of Clearance: April 06, 2021

Invitation

You are invited to take part in a research project because you were interested 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. 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.

Purpose of the study

Investigates the best way to integrate a smartphone as an input and display device in VR.
Researches the possibility of novel smartphone interaction in VR.
Investigates methods to provide large tactile surfaces in VR/MR using small physical surfaces.
Increases the possible usability of smartphone-based VR headsets, which currently offers limited interaction possibilities

Request edit access

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

This study takes place in one approximately 60-minute session, completely remotely. You will not be audio or videotaped.
The user study is based on the 2D selection task using a smartphone in VR.

In this user study, you should select the round targets which are displayed on the smartphone model. You will see the smartphone model tracking the position of a real smartphone in VR. You should hold a smartphone in one hand and wear a head-mounted display. You should select the targets as fast as possible on the smartphone touchscreen with your thumb.

For the study you will need:
Equipment:
First Android smartphone for hand input (SHI)
Second Android smartphone for VR view (SVR) with Internet access (to send logs)
Google Cardboard or similar low-cost VR display that requires a smartphone be inserted (provided by the researcher via mail)
Armchair or chair with armrests.

You will be asked to provide your mailing address for us to be able to send you a VR display. We will not keep your mailing address and destroy this data after the sending of the VR display.
We will also ask you to provide your Skype or Discord id, to be able to contact you during the user study and help with the instructions. We will destroy this data after the study.
You will be asked to install apps on your smartphones to see the VR environment and select targets on the smartphone. Detailed instructions will be provided and the researcher will consult you during the process of the study.
You will be asked to complete a questionnaire before, during, and after the study.

Risks and Inconveniences

Like all stereo 3D display systems, there is some small risk of minor eye discomfort. Like all VR systems, there is a small risk of experiencing cybersickness, or visually induced motion sickness. We have taken efforts to avoid these issues by keeping you seated and stationary (i.e., little or no physical movement is required in the VR system, which should largely eliminate the risk of cybersickness). If you experience any symptoms, please to take a break until you feel fine. In the unlikely event of extreme reactions, please withdraw from the experiment (you are still free to keep the VR head-mounted display).

Possible Benefits

You have the opportunity to try a potentially interesting VR system and help improve the state of interactions on low-cost VR devices

Compensation

You will be compensated with the smartphone-based VR head-mounted display that will be sent to you for the study (you can keep it).

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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

You can withdraw during the experiment (i.e., not complete it), but after the completion withdrawal is not possible as we are not keeping any personal data linking their results to your identity.

Confidentiality

Data will be de-identified (anonymized) with any identifiers securely destroyed. Anonymized data will be kept for use in presentations and publications.

"In-session" data, such as the audio, video and chat transcript from the interview, will be stored locally on the researcher's computer. Operation data, such as meeting and performance data, will be stored and protected by Skype or Discord on servers located in Austria (Vienna), Finland (Helsinki), France (Paris, Marseille), Ireland (Dublin), Netherlands (Amsterdam), Canada (Quebec City, Toronto) for Skype and Germany (Frankfurt), United States (New York City), but may be disclosed via a court order or data breach.

We will encrypt any research data that we store or transfer.

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 email at ethics@carleton.ca).

Type your name here *

Your answer

Request edit access

I voluntarily agree to participate in this study *

Yes

No

Date *

MM DD YYYY

/ /

Submit

Never submit passwords through Google Forms.

Request edit access

Appendix B User Instructions

B.1 User Study 1 Instructions for participants

Instruction for participant Study 1

The user study is based on the 2D selection task using a smartphone in smartphone-based "cardboard" VR. In this user study, you should select the round targets which are displayed on the smartphone model. You will see the smartphone model tracking the position of a real smartphone in VR. You should hold a smartphone in one hand and wear a head-mounted display. You should select the targets as fast as possible on the smartphone touchscreen with your thumb.

There are 2 conditions and 6 study blocks, 3 for each condition. Each study block has 10 sequences of 15 targets each. Conditions:

1) Direct – The smartphone screen is on the device.
2) Indirect – The smartphone screen is placed in front of the user.

Conditions go one after another, which one first depends on your participant number.

In the beginning, you have 3 sequences with the direct condition to practice.

Remember we are going to test the prototype, not you!

User study instructions:

Devices needed:

1) Smartphone for hand input (SHI)
2) Smartphone for VR view (SVR) with Internet access (to send logs)
3) Smartphone-based VR head-mounted display, referring further as “VR box”.
4) Armchair or chair with armrests

Installation procedure:

1) Read this document till the end.
2) Sign the consent form. Link:

https://forms.gle/ys4x9p6z3NHHyqvg7

3) Open the Google Form and fill out the first topic (ask for participant id). Link:

https://forms.gle/KCK3ZCf68BUVMLtK9

4) Install Cardboard app from Google Play Store, Link:

https://play.google.com/store/apps/details?id=com.google.samples.apps.cardboarddemo

5) Install RTC.apk and Fitts.apk on the SHI. Links:

https://drive.google.com/file/d/1cc_Jq0ZGxzJ6tNeguCYf3ZorlKdrHzAA/view?usp=sharing

https://drive.google.com/file/d/1mYbFdo635Qn8gtfrI2I2MItC8z1OJV3W/view?usp=sharing

6) Install VRPhone.apk on the SVR. Link:

https://drive.google.com/file/d/1A-UWaqCQeg5B85CQl9C6UJM38nIqQTI0/view?usp=sharing

7) Put both SVR and SHI in Silent mode.
8) Share Wi-Fi network from SVR, connect SHI to the shared network. If it's supported by your smartphone, keep enabled the Wi-Fi connection of SVR to a router with Internet access as well.
9) Run the RTC app, allow the permissions if needed, press Start Now.
10) Close all the apps on the SVR to reduce RAM and CPU load. Run the VRPhone app on the SVR, allow the permissions if needed, direct the phone camera on the SHI screen to scan the QR-Code from SHI.
11) Hide the RTC app and open Fitts app on the SHI.
12) **Select Participant Id, Study Number 1, and Condition that will be told**, press Run Experiment.
13) Direct the SVR camera on the SHI screen to find the SHI position.
14) After the loading, click the icon, select "Scan QR-code" or "Switch Viewer" and scan the QR-code of the VR box:

15) Put the SVR phone into VR box, the phone's camera should be closer to your dominant hand for better tracking (default orientation when the camera is closer to the left, you may need to turn the phone to change it). Make sure the SVR camera has no obscurity.
16) Sit, place the SHI phone in front of you on the table, where you will be able to take the phone without seeing it.
17) Put the VR box on, adjust straps and lenses. If your VR box with the device inside is too heavy and makes you

uncomfortable you can use your non-dominant hand to hold it.

18) Take the SHI in your dominant hand. Put the little finger under the phone to be able to hold it with one hand while selecting targets with your thumb. Put your dominant hand’s forearm on the armrest. The correct hand position showed in this photo:

19) Point your head to the position of SHI and make sure the app can trace it.
20) Start the experiment practice by double-tap.
21) Make 3 first sequences, press back, **remove checkbox “Is Test”**, press Run Experiment, and double-tap.
22) Complete the first 3 blocks (you can remove the headset to take the rest for a couple of minutes after the end of each block).
23) Remove the headset, fill out the topic of the condition, which you just used (second or third topic) in the Google Form (there will be a hint when to do it).
24) Put the headset back, complete another three blocks, wait in the end for logs to send.
25) Fill out the topic about the second condition and the final topic in the Google Form and send it.

Thank you for the participation!

B.2 User Study 2 Instructions for participants

Instruction for participant Study 2

The user study is based on the 2D selection task using a smartphone in smartphone-based “cardboard” VR. In this user study, you should select the round targets which are displayed on the smartphone model. You will see the smartphone model tracking the position of a real smartphone in VR. You should hold a smartphone in one hand and wear a head-mounted display. You should select the targets as fast as possible on the smartphone touchscreen with your thumb.

The sequences of targets will be with different scale factors – degree of surface warping, similar to different mouse sensitivity on PC.

There are 8 different scale factors – 1 block each. Each study block has 8 sequences of 15 targets each.

At the start, you will have 3 sequences with no scaling to practice.

Remember we are going to test the prototype, not you!

User study instructions:

Devices needed:

1) Smartphone for hand input (SHI)
2) Smartphone for VR view (SVR) with Internet access (to send logs)
3) Smartphone-based VR head-mounted display, referring further as “VR box”.
4) Armchair or chair with armrests

Installation procedure:

1) Read this document till the end.
2) Sign the consent form. Link:

https://forms.gle/ys4x9p6z3NHHyqvg7

3) Open the Google Form and fill out the first topic (ask for participant id). Link:

https://forms.gle/TGzjmsVkTkSVvzMu7

4) Install Cardboard app from Google Play Store, Link:

https://play.google.com/store/apps/details?id=com.google.samples.apps.cardboarddemo

5) Install RTC.apk and Fitts.apk on the SHI. Links:

https://drive.google.com/file/d/1cc_Jq0ZGxzJ6tNeguCYf3ZorlKdrHzAA/view?usp=sharing

https://drive.google.com/file/d/1mYbFdo635Qn8gtfrI2I2MItC8z1OJV3W/view?usp=sharing

6) Install VRPhone.apk on the SVR. Link:

https://drive.google.com/file/d/1A-UWaqCQeg5B85CQl9C6UJM38nIqQTI0/view?usp=sharing

7) Put both SVR and SHI in Silent mode.
8) Share Wi-Fi network from SVR, connect SHI to the shared network. If it's supported by your smartphone, keep enabled the Wi-Fi connection of SVR to a router with Internet access as well.
9) Run RTC app, allow the permissions if needed, press Start Now
10) Close all the apps on the SVR to reduce RAM and CPU load. Run the VRPhone app on the SVR, allow the permissions if needed, direct the phone camera on the SHI screen to scan the QR-Code from SHI.
11) Hide the RTC app and open Fitts app on the SHI.
12) **Select Participant Id, Study Number 2**, press Run Experiment.
13) Direct the SVR camera on the SHI screen to find the SHI position.
14) After the loading, click the icon, select "Scan QR-code" or "Switch Viewer" and scan the QR-code of the VR box:

15) Put the SVR phone into VR box, the phone's camera should be closer to your dominant hand for better tracking (default orientation when the camera is closer to the left, you may need to turn the phone to change it). Make sure the SVR camera has no obscurity.
16) Sit, place the SHI phone in front of you on the table, where you will be able to take the phone without seeing it.
17) Put the VR box on, adjust straps and lenses. If your VR box with the device inside is too heavy and makes you

uncomfortable you can use your non-dominant hand to hold it.

18) Take the SHI in your dominant hand. Put the little finger under the phone to be able to hold it with one hand while selecting targets with your thumb. Put your dominant hand's forearm on the armrest. The correct hand position showed in this photo:

19) Point your head to the position of SHI and make sure the app can trace it.
20) Start the experiment practice by double-tap.
21) Make 3 first sequences, press back, **remove checkbox "Is Test"**, press Run Experiment, and double-tap.
22) Complete the experiment (you can remove the headset to take the rest for a couple of minutes after the end of each block).
23) Fill out the final topic in the Google Form and send it.

Thank you for the participation!

Appendix C Questionnaires

C.1 User Study 1 Questionnaire

Study 1 Smartphone Selection in VR Research Questionnaire

Please answer the following questions about the smartphone selection study:

* Required

First topic: The following questions are demographic

Participant number *

Your answer

Age *

Your answer

Gender *

- ○ Male
- ○ Female
- ○ Other:

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How often do you experience VR? *

- 5 - Every day
- 4 - Several times a week
- 3 - Several times a month
- 2 - Several times a year
- 1 - Never

What is your dominant hand? *

- Right hand
- Left hand

Second topic: The following questions relate to the DIRECT condition of smartphone selection

Physical effort required *

- 5 - very low
- 4 - low
- 3 - average
- 2 - high
- 1 - very high

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Fast selection was *

- 5 - very easy
- 4 - easy
- 3 - average
- 2 - hard
- 1 - very hard

Accurate selection was *

- 5 - very easy
- 4 - easy
- 3 - average
- 2 - hard
- 1 - very hard

General comfort *

- 5 - very comfortable
- 4 - comfortable
- 3 - average
- 2 - uncomfortable
- 1 - very uncomfortable

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Third topic: The following questions relate to the INDIRECT condition of smartphone selection

Physical effort required *

- 5 - very low
- 4 - low
- 3 - average
- 2 - high
- 1 - very high

Fast selection was *

- 5 - very easy
- 4 - easy
- 3 - average
- 2 - hard
- 1 - very hard

Request edit access

Accurate selection was *

- 5 - very easy
- 4 - easy
- 3 - average
- 2 - hard
- 1 - very hard

General comfort *

- 5 - very comfortable
- 4 - comfortable
- 3 - average
- 2 - uncomfortable
- 1 - very uncomfortable

Final topic: Final questions

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The force required for actuation was *

- 5 - very low
- 4 - low
- 3 - average
- 2 - high
- 1 - very high

Smoothness during operation was *

- 5 - very smooth
- 4 - smooth
- 3 - average
- 2 - rough
- 1 - very rough

The mental effort required for operation was *

- 5 - very low
- 4 - low
- 3 - average
- 2 - high
- 1 - very high

Request edit access

The physical effort required for operation was *

- 5 - very low
- 4 - low
- 3 - average
- 2 - high
- 1 - very high

Accurate pointing was *

- 5 - very easy
- 4 - easy
- 3 - average
- 2 - difficult
- 1 - very difficult

Operation speed was *

- 5 - very fast
- 4 - fast
- 3 - average
- 2 - slow
- 1 - very slow

Request edit access

Finger fatigue: *

- 5 - none
- 4 - small fatigue
- 3 - average fatigue
- 2 - high fatigue
- 1 - very high fatigue

Wrist fatigue: *

- 5 - none
- 4 - small fatigue
- 3 - average fatigue
- 2 - high fatigue
- 1 - very high fatigue

Arm fatigue: *

- 5 - none
- 4 - small fatigue
- 3 - average fatigue
- 2 - high fatigue
- 1 - very high fatigue

Request edit access

Shoulder fatigue: *

- 5 - none
- 4 - small fatigue
- 3 - average fatigue
- 2 - high fatigue
- 1 - very high fatigue

Neck fatigue: *

- 5 - none
- 4 - small fatigue
- 3 - average fatigue
- 2 - high fatigue
- 1 - very high fatigue

General comfort *

- 5 - very comfortable
- 4 - comfortable
- 3 - average
- 2 - uncomfortable
- 1 - very uncomfortable

Request edit access

Overall, the input device was *

- 5 - very easy to use
- 4 - easy to use
- 3 - average difficulty to use
- 2 - difficult to use
- 1 - very difficult to use

You may give other feedback about the study here

Your answer

Submit

C.2 User Study 2 Questionnaire

Study 2 Smartphone Selection in VR Research Questionnaire

Please answer the following questions about the smartphone selection study:

* Required

First topic: The following questions are demographic

Participant number *

Your answer

Age *

Your answer

Gender *

- ◯ Male
- ◯ Female
- ◯ Other:

Request edit access

How often do you experience VR? *

- 5 - Every day
- 4 - Several times a week
- 3 - Several times a month
- 2 - Several times a year
- 1 - Never

What is your dominant hand? *

- Right hand
- Left hand

Final topic: Final questions

How, in your opinion, the different scale factors influenced your performance? *

- 5 - No influence
- 4 - Small influence
- 3 - Average influence
- 2 - Strong influence
- 1 - Very strong influence

Request edit access

The force required for actuation was *

- 5 - very low
- 4 - low
- 3 - average
- 2 - high
- 1 - very high

Smoothness during operation was *

- 5 - very smooth
- 4 - smooth
- 3 - average
- 2 - rough
- 1 - very rough

The mental effort required for operation was *

- 5 - very low
- 4 - low
- 3 - average
- 2 - high
- 1 - very high

Request edit access

The physical effort required for operation was *

- 5 - very low
- 4 - low
- 3 - average
- 2 - high
- 1 - very high

Accurate pointing was *

- 5 - very easy
- 4 - easy
- 3 - average
- 2 - difficult
- 1 - very difficult

Operation speed was *

- 5 - very fast
- 4 - fast
- 3 - average
- 2 - slow
- 1 - very slow

Request edit access

Finger fatigue: *

- 5 - none
- 4 - small fatigue
- 3 - average fatigue
- 2 - high fatigue
- 1 - very high fatigue

Wrist fatigue: *

- 5 - none
- 4 - small fatigue
- 3 - average fatigue
- 2 - high fatigue
- 1 - very high fatigue

Arm fatigue: *

- 5 - none
- 4 - small fatigue
- 3 - average fatigue
- 2 - high fatigue
- 1 - very high fatigue

Request edit access

Shoulder fatigue: *

- 5 - none
- 4 - small fatigue
- 3 - average fatigue
- 2 - high fatigue
- 1 - very high fatigue

Neck fatigue: *

- 5 - none
- 4 - small fatigue
- 3 - average fatigue
- 2 - high fatigue
- 1 - very high fatigue

General comfort *

- 5 - very comfortable
- 4 - comfortable
- 3 - average
- 2 - uncomfortable
- 1 - very uncomfortable

Request edit access

Overall, the input device was *

- 5 - very easy to use
- 4 - easy to use
- 3 - average difficulty to use
- 2 - difficult to use
- 1 - very difficult to use

You may give other feedback about the study here

Your answer

Submit

Appendix D Posters

D.1 User Study 1 Poster

Smartphone Selection in VR User Study 1

What types of smartphone screen position in VR are more efficient

Study Title: Selection Performance Using a Smartphone in VR with Redirected Input

Researcher: Stanislav Kyian

Supervisor: Robert Teather

We are looking for participants for a selection performance study in VR.

The user study is based on the 2D selection task using a smartphone in smartphone-based "cardboard" VR. In this user study, you should select the round targets which are displayed on the smartphone model. You will see the smartphone model tracking the position of a real smartphone in VR. You should hold a smartphone in one hand and wear a head-mounted display. You should select the targets as fast as possible on the smartphone touchscreen with your thumb.

Conditions:

Direct – The smartphone screen is on the device.

Indirect – The smartphone screen is placed in front of the user.

Following the experiment, participants will be asked to evaluate each condition.

You will need to install applications provided by researcher on your smartphones to setup the experiment. Applications will record your selection performance. No audio or video recordings will be done.

The study will be conducted entirely online.

Session should take approximately 60 minutes to complete. To be eligible, you must be an adult (over the age of 18), be able to communicate in English and have 2 Android smartphones. Smartphone-based "cardboard" VR headset will be provided via mail. You will be able to keep the provided device.

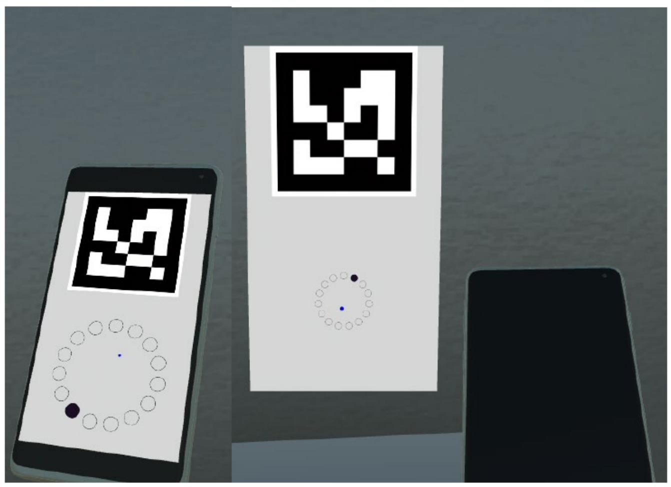
This research has been cleared by Carleton University Research Ethics Board-B (CUREB-B Clearance # 115464).

If you are interested, please e-mail Stanislav Kyian at stanislavkyian@cmail.carleton.ca for more details.

D.2 User Study 2 Poster

Smartphone Selection in VR User Study 2

Does the virtual warped surface influence the selection performance in VR



Study Title: Selection Performance Using a Smartphone in VR with Redirected Input

Researcher: Stanislav Kyian

Supervisor: Robert Teather

We are looking for participants for a selection performance study in VR.

The user study is based on the 2D selection task using a smartphone in smartphone-based "cardboard" VR. In this user study, you should select the round targets which are displayed on the smartphone model. You will see the smartphone model tracking the position of a real smartphone in VR. You should hold a smartphone in one hand and wear a head-mounted display. You should select the targets as fast as possible on the smartphone touchscreen with your thumb.

The sequences of targets will be with different scale factors – degree of surface warping, similar to different mouse sensitivity on PC.

Following the experiment, participants will be asked to evaluate the scale factors influence.

You will need to install applications provided by researcher on your smartphones to setup the experiment. Applications will record your selection performance. No audio or video recordings will be done.

The study will be conducted entirely online.

Session should take approximately 60 minutes to complete. To be eligible, you must be an adult (over the age of 18), be able to communicate in English and have 2 Android smartphones. Smartphone-based "cardboard" VR headset will be provided via mail. You will be able to keep the provided device.

This research has been cleared by Carleton University Research Ethics Board-B (CUREB-B Clearance # 115464).

If you are interested, please e-mail Stanislav Kyian at stanislavkyian@cmail.carleton.ca for more details.

Appendix E Letter of invitation

Subject:

User study participation

Text:

Carleton UNIVERSITY

Hello <potential participant name>,

I would like to invite you to participate in a selection performance study in VR.

Study Title: Selection Performance Using a Smartphone in VR with Redirected Input

Researcher: Stanislav Kyian

Supervisor: Robert Teather

The study will be completely remote. The session should take approximately 60 minutes to complete. To be eligible, you must be an adult (over the age of 18), be able to communicate in English, and have 2 Android smartphones. Smartphone-based "cardboard" VR headset will be provided via mail. You will be able to keep the provided device.

The user study is based on the 2D selection task using a smartphone in smartphone-based "cardboard" VR. In this user study, you should select the round targets which are displayed on the smartphone model. You will see the smartphone model tracking the position of a real smartphone in VR. You should hold a smartphone in one hand and wear a head-mounted display. You should select the targets as fast as possible on the smartphone touchscreen with your thumb.

Following the experiment, you will be asked to answer questionnaire about the study.

You will need to install applications provided by researcher on your smartphones to setup the experiment. Applications will record your selection performance. No audio or video recordings will be done.

The study will be conducted entirely online.

Session should take approximately 60 minutes to complete. To be eligible, you must be an adult (over the age of 18), be able to communicate in English and have 2 Android smartphones. Smartphone-based "cardboard" VR headset will be provided via mail. You will be able to keep the provided device.

This research has been cleared by Carleton University Research Ethics Board-B (CUREB-B Clearance # 115464).

If you are interested, please read and fill out this consent form:

https://forms.gle/8oVhL4fAWXgSmpLW7

If you agreed to participate in the consent form, please send me your Skype or Discord Id to contact you during the study, and your postal address to send you the equipment (smartphone-based “cardboard” head-mounted display) in the reply to this email.

Best regards,

Stanislav

Appendix F CUREB Documents

F.1 CUREB Very Low Risk Form

Office of Research Ethics
CARLETON UNIVERSITY

RESEARCH INVOLVING VERY LOW RISK

This Form is for research projects meeting *all* the following criteria. If you have any doubt about whether your study may use this form, or questions about its completion, please contact the Research Ethics Office at ethics@carleton.ca or by phone to 613 520 2600 ext. 2517 (CUREB A) or ext. 4085 (CUREB B).

1. The risks to participants are very low;
2. No research procedures involve any physically invasive intervention;
3. Participants are legally capable of consenting on their own behalf, and are free from coercion or undue influence;
4. Any accidental or intentional disclosure of the participants' responses would not reasonably place participants at risk of criminal or civil liability, harmful retaliation, or be damaging to the participants' emotional or financial well-being, employability, or reputation;
5. The study does not involve recruitment by a third party aside from a paid research service such as Qualtrics or Survey Monkey; and
6. The study does not involve deception or providing incomplete information to participants.
7. This study does not primarily involve Indigenous peoples or communities.

If the project does not meet all of these conditions, then the main CUREB Protocol Form must be used.

* Please submit the Very Low Risk form as a new application in CuResearch. If this form is to replace a Release of Funds, it should be submitted as an "Event" in CuResearch under the same study file. Please see our CuResearch User Manual for directions on how to submit a new application or an event.

* Note that all of our forms are compatible with Microsoft Office. Students and staff members can download a free copy of MS Office at no charge: Students: https://carleton.ca/its/ms-offer-students/ ; Staff/Faculty: https://carleton.ca/its/all-services/computers/site-licensed-software/ms-offer-faculty/

1.	Title and Date

1A **Project Title**

Selection Performance Using a Smartphone in VR with Redirected Input

1B **Submission Date** Date of completion of this form. Update each time the form is revised.

4/1/2021

2.	Project Team

2A **Lead Researcher** Last name/First name, Institutional Email, Department/Faculty and Institution if not Carleton

- ☐ Academic or Library Staff
- ☐ Post-doctoral Fellow
- ☐ Doctoral Student
- ☒ Masters Student

Kyian/Stanislav, stanislavkyian@cmail.carleton.ca, School of Information Technology

If other, please describe

☐	Undergraduate Student	
☐	Other	

2B **Academic Supervisor**

☐ Same as lead researcher

Academic supervisor(s) Last name/First name, Institutional Email, Department/Faculty and Institution if not Carleton (Note, the supervisor must be copied on all correspondence with CUREB.) (Detailed instructions, Example)

Teather/Robert, Rob.Teather@carleton.ca, School of Information Technology

2C **Project Team Members**

☒ No other team members

List the project team members: 1) Last name/First name 2) Email address 3) Role in project 4) Department and institution (Detailed instructions, Example)

3. Project Description

3A **Is this Project Funded?**

☒ Yes

☐ No

If Yes, who is the award provided by, and what is the title of the award?

Supervisor's NSERC Discovery Grant – 315034: Towards Walk-Up Usable 3D User Interfaces

3B **Study Goal**

Briefly explain the primary objective(s) of the current study.

This study:

- Conduct a research for a master's thesis
- Investigates the best way to integrate a smartphone as an input and display device in VR.
- Researches the possibility of novel smartphone interaction in VR.
- Investigates methods to provide large tactile surfaces in VR/MR using small physical surfaces.
- Increases the possible usability of smartphone-based "cardboard" VR display, which currently offers limited interaction possibilities

3C **Study Rationale and Expected Benefits**

Study Rationale and Expected Benefits: Why should the study be done? What are the benefits, and to whom?

Current "cardboard" VR displays (e.g., Google Cardboard) are cheap and easily accessible, requiring only a smartphone to provide an immersive virtual reality experience. They are thus promising as a hardware platform for the widespread deployment of VR applications such as education (e.g., remote learning in VR), training (e.g., surgical simulation), and entertainment. However, they offer limited interaction capabilities due to the absence of a separate "wand-like" input device provided with more full-featured devices like the Oculus Rift. The rationale of the current study is to investigate the use of a secondary smartphone as a tactile tablet-like surface used in combination with a cardboard HMD, to investigate interaction possibilities and performance capabilities offered.

To date, there have been relatively few studies on touch input using smartphones in VR. Only a few studies have used a smartphone as an input method in VR. There are currently virtually no mobile apps that allow using the smartphone from VR (consider that currently e.g., answering a call on a smartphone requires context switching and removing the head-mounted display (HMD), which can cause disengagement from the task and increase the probability of cybersickness).

The results of the study benefit the VR headset developers and users of VR systems and applications, providing insight into how to implement novel interactions in the VR Headsets. The study also benefits VR researchers because it provides information about using smartphones in VR with input/output as well as scaled tactile surfaces performance influence.

3D **Overview of Methodology and Participant Interactions**

Briefly describe the study methodology and what will be required of participants for this study

The experiment will be conducted remotely and will involve no person-to-person contact due to the ongoing COVID-19 pandemic. All equipment will be direct ordered online to participants, and the software will be provided via a download link. Instructions and consultation with the experimenter will be done via online communication tools. The experiment will take approximately 60 minutes, where participants will experience VR for around 45 minutes. Participants will see a virtual 3D smartphone model corresponding to the position of a real (tracked) smartphone in VR. Participants will hold a smartphone in one hand and while wearing the provided head-mounted display. The software will display circular targets on the smartphone model in VR; Participants will select these targets (i.e., tap them), while the software tracks their selection speed and accuracy.

For the study preparation participant will need:

- An Android smartphone for hand input (SHI)
- A Second Android smartphone for VR view (SVR) with Internet access (to send logs)

- Google Cardboard, or similar low-cost VR display that requires a smartphone be inserted (provided by the researcher via mail)
- Armchair or chair with armrests.

The low-cost VR display is a plastic box with lenses and the place for the smartphone at the front side (to use it as a display). It will be ordered for the participants by the researcher. Images and descriptions of the equipment are included in the attachments in the "SoftwareAndHardwareDescription.docx" file.

The researcher will call the participants using IP-telephony (Skype or Discord) to help them follow the instructions. They will be instructed on how to set up the cardboard HMD, download and setup the software. This will all be done remotely – there is no in-person interaction.

Participants should provide their mailing address for us to be able to send them a cardboard HMD. We will not keep their address and destroy this data after the sending.

Participants should provide their Skype or Discord id, which we will use to contact them during the user study and help with the instructions. We will destroy this data after the user study.

Participants will install apps on their smartphones to see the VR environment and select targets on the smartphone.

"APK" installation files of the apps are available from Google Drive.

Apps that should be installed are:

1) VRPhone app on the smartphone for VR view, which shows virtual environment with the translated screen of the second smartphone in it.
2) Fitts app, which allows configuring the study, shows the targets to select and gathers logs about the selection performance.
3) RTC app, which translates the smartphone screen from the smartphone for hand input to the smartphone for VR view via local Wi-Fi network.

Screenshots of the apps and links to download them are included in the attachments in the "SoftwareAndHardwareDescription.docx" file.

Detailed instructions are included in the attachments.

At least 12 participants, who will apply first (or more, depending on how many will be interested) will be assigned to do study 1. Next participants will be assigned to do study 2.

4. Participants and Informed Consent

4A **Description of Participants**

Describe the participants and any inclusion and exclusion criteria. If using a separate sample of control participants, describe this group. (Detailed instructions, Example)

Inclusion criteria:

Have no history of nausea or dizziness with virtual reality use.

18 years old or older with regular stereo viewing capability (i.e., can perceive 3D effects).

Have access to the required equipment:

2 Android smartphones and armchair or chair with armrests.

4B	**Number of Participants (Sample size)**	How many participants will be recruited? If multiple groups of participants are involved, breakdown by participant type. Provide a justification including a statistical rationale if appropriate. (Detailed instructions, Example)

I am going to recruit up to 50 participants.

4C	**Recruitment**	Describe how participants will be recruited including how contact information will be obtained. How will participants be made aware of the study, where will recruitment materials be located, and how may participants express their interest? Attach a copy of any recruitment materials including oral scripts, recruitment posters, emails and social media postings, etc.

I will post the recruitment on the Carleton Research Participants Facebook page, the post example provided in the attachment. I will also recruit people by sending the letter of invitation (attached) via email to people, who might be interested. The contact information (Skype or Discord Id) and mailing address will be asked on the email of invitation (attached). The email of invitation will be sent from the Carleton email account. We ask participants to send them in the reply to the email of invitation, if they read and accepted the consent form.

We intend to send an email to personal contacts.

4D	**Compensation and Remuneration**	Describe any compensation or remuneration for participants and indicate when participants will receive the compensation. What happens to compensation if a participant withdraws early?

The provided cardboard HMD will be a gift to participants to keep following completion of the experiment. We will not request these to be returned.

Participants will be recruited both in Canada and Ukraine. For the Canadian participants the HMD costs $30 CAD, here is the link:

https://www.amazon.ca/gp/product/B08RDLKG4G

For the Ukrainian participants the HMD costs 300 UAH, roughly $15 CAD, here is the link:

https://rozetka.com.ua/ua/132341843/p132341843

(the models are insignificantly different)

The researcher will pay for this out of pocket and then get reimbursed according to the paying bills.

4E	**Withdrawal Process**	Describe the process for a participant to withdraw their data after collection, and the time limits, if any. Participants can withdraw during the experiment (i.e., not complete it), but after the completion withdrawal is not possible as we are not keeping any personal data linking their results to their identity.
4F	**Consent**	Describe the process of obtaining informed consent from participants and include a copy of the consent form(s) and materials. If signed consent is not to be used, describe and justify the alternative method chosen. The consent form will be in the form of Google Forms to be able to make the study fully remote. The same consent form will be used for study 1 and study 2. See attached form.
4G	**Risks**	Describe any possible physical, emotional, social, privacy, or legal risks to which participants may be exposed. Like all stereo 3D display systems, there is some small risk of minor eye discomfort. Like all VR systems, there is a small risk of experiencing cybersickness, or visually induced motion sickness. We have taken efforts to avoid these issues by keeping the participant seated and stationary (i.e., little or no physical movement is required in the VR system, which should largely eliminate the risk of cybersickness). If participants experience any symptoms, they will be encouraged to take a break until they feel fine. In the unlikely event of extreme reactions, participants will be recommended to withdraw from the experiment (and will be free to keep the cardboard head-mounted display).

4H	**Vulnerable Participants**	Does the research project target participants from vulnerable populations (e.g., children, elderly, or prisoners), involve sensitive questions, include partial disclosure and/or mild deception, involve physical exertion, physical procedures or physical contact? If yes, justify why the project(s) still falls within the parameters of very low risk. ☐ Yes ☒ No

5.	**Data Collection, Use, and Storage**

5A	**Collection**	Describe how data will be collected and any instruments to be used. Provide a copy of any questionnaires, surveys, interview guides or other data collection materials.

People will contact the researcher via email if they are interested to participate, that way the researcher got their email and can email them the details in a response letter.

The contact information (Skype or Discord Id) and mailing address will be asked on the email of invitation (attached). The email of invitation will be sent from the Carleton email account. We ask participants to send them in the reply to the email of invitation, if they read and accepted the consent form.

Participants will evaluate the study conditions via the Google Forms questionnaire (attached).

The Fitts App, which participants install on the smartphone collects the start time, movement time, and error rate in the selection study, which is automatically sent to the researcher via email at the end of the study. Other apps don't collect any data.

5B	**Access**	Aside from the PI, who will have access to research data?

Nobody.

5C	**Identifiability**	Describe the identifiability of research data, including how codes or pseudonyms will be assigned

☐	Data will contain information that directly identifies participants.
☐	Data will contain information that may indirectly identify participants.
☐	Data will be coded with the code key stored securely and separate from identifying information.
☒	Data will be de-identified (anonymized) with any identifiers securely destroyed.

Provide any further relevant detail about the identifiability of data.

The researcher asks a participant to put a designated participant number in the Google Form survey and in the Fitts (selection task) app to de-identify the data. There is not any identifiable information included in the survey, or in the app. The recordings will not be taken through Skype/Discord.

In order to anonymize the data, the researcher will tell to the participant a random 3-digit number, that he should enter in the app and in the questionnaire. The data from the app and questionnaire will only contain that number.

5D **Data Security**

Describe the physical (e.g. locked filing cabinet) and/or technical safeguards (e.g. Encryption) that will be used to securely store the collected physical and electronic data. Where will data be stored?

The anonymized data will be sent via email to the researcher's account and stored on the researcher's email account and PC. It will be used for academic credit and may be used for publications and presentations. This data will not be removed.

Contact information, skype/discord information, and mailing address will be stored as emails on the Carleton email account and will be removed after the study.

5E Does your research involve the use of ***personal data*** held by Carleton? If yes, you must complete a *security and confidentiality agreement* with the Carleton University Privacy Office prior to starting your research. The agreement is a contract between you and the university as to how you will manage the personal data throughout your research. If you have questions about the completion of this agreement, or best practices around privacy management for research, please contact the Carleton University Privacy Office by e-mail at *university_privacy_office@carleton.ca*.

Yes ☐ No ☒

If yes, please describe the personal information you will be collecting:

6. Attachments

6A Please indicate any attached materials.

☒	TCPS 2 Tutorial Course on Research Ethics (CORE) tutorial certificate for each team member. if requesting exemption, please justify below
☒	Sample of data collection instruments (survey questionnaires, test instruments, ect.)
☒	Supervisor approval form (if applicable)
☐	Permission letter from partner organizations (if applicable)
☐	Letters of Invitation/Information
☒	Consent forms, text or scripts
☒	Debriefing form
☐	Other, please describe in the following box

6B Provide a brief rationale if an attachment(s) is not available at time of submission.

7. Declarations

By submitting this form, the Lead Researcher and academic supervisor, if any, confirm that:

- The information in this Form is correct and accurately describes the research project.
- No recruitment or data collection for this protocol will start before receiving ethics clearance.
- I (we) will carry out this project in accordance with the information in this Form and the other submitted documents. No changes will be made to the research project as described in this protocol without clearance from the Research Ethics Board.
- I will promptly notify the Research Ethics Board of any ethical breaches or concerns, adverse events, unanticipated problems, protocol deviations or complaints that arise relating to this project.
- This study meets all of the conditions for eligibility listed above.

8. Comments

Do you have any comments or suggestions to improve this form?

F.2 CUREB Software and Hardware Description

Hardware:

VR Shinecon (model may be insignificantly different)

Picture:

In the opened state (place for the smartphone is opened):

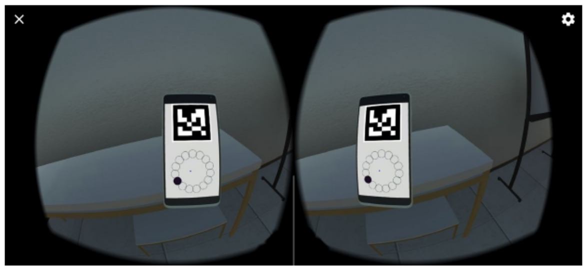
Software:

1) VRPhone app on the smartphone for VR view, which shows virtual environment with the translated screen of the second smartphone in it.

Link:

https://drive.google.com/file/d/1A-UWaqCQeg5B85CQl9C6UJM38nIqQTI0/view?usp=sharing

Screenshot:

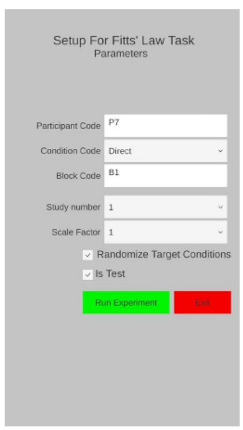


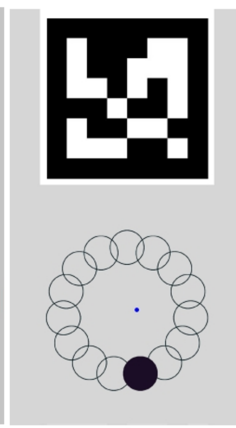
2) Fitts app, which allows configuring the study, shows the targets to select and gathers logs about the selection performance.

Link:

https://drive.google.com/file/d/1mYbFdo635Qn8gtfrI2I2MItC8z1OJV3W/view?usp=sharing

Screenshots:



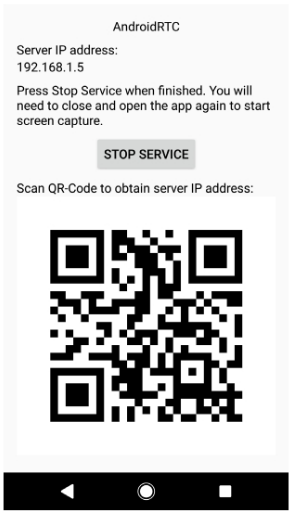


3) RTC app, which translates the smartphone screen from the smartphone for hand input to the smartphone for VR view via local Wi-Fi network.

Link:

https://drive.google.com/file/d/1cc_Jq0ZGxzJ6tNeguCYf3ZorlKdrHzAA/view?usp=sharing

Screenshot:



References

1. Haley Adams, Gayathri Narasimham, John Rieser, Sarah Creem-Regehr, Jeanine Stefanucci, and Bobby Bodenheimer. 2018. Locomotive recalibration and prism adaptation of children and teens in immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics* 24, 4: 1408–1417. https://doi.org/10.1109/TVCG.2018.2794072
2. Marylyn Alex, Danielle Lottridge, Jisu Lee, Stefan Marks, and Burkhard Wüensche. 2020. Discrete versus Continuous Colour Pickers Impact Colour Selection in Virtual Reality Art-Making. *ACM International Conference Proceeding Series*, Figure 2: 158–169. https://doi.org/10.1145/3441000.3441054
3. Tatsuya Amano, Shugo Kajita, Hirozumi Yamaguchi, Teruo Higashino, and Mineo Takai. 2018. Smartphone applications testbed using virtual reality. *ACM International Conference Proceeding Series*: 422–431. https://doi.org/10.1145/3286978.3287028
4. Vladislav Angelov, Emiliyan Petkov, Georgi Shipkovenski, and Teodor Kalushkov. 2020. Modern Virtual Reality Headsets. *HORA 2020 - 2nd International Congress on Human-Computer Interaction, Optimization and Robotic Applications, Proceedings*. https://doi.org/10.1109/HORA49412.2020.9152604
5. Roland Arsenault and Colin Ware. 2000. Eye-hand co-ordination with force feedback. *Conference on Human Factors in Computing Systems - Proceedings* 2, 1: 408–414. https://doi.org/10.1145/332040.332466
6. Jasmine R Aziz, Stephane J MacLean, Olave E Krigolson, and Gail A Eskes. 2020.

Visual Feedback Modulates Aftereffects and Electrophysiological Markers of Prism Adaptation . *Frontiers in Human Neuroscience 14*, 138. Retrieved from https://www.frontiersin.org/article/10.3389/fnhum.2020.00138

7. Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. 2016. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. *Conference on Human Factors in Computing Systems - Proceedings*: 1968–1979. https://doi.org/10.1145/2858036.2858226
8. Huidong Bai, Li Zhang, Jing Yang, and Mark Billinghurst. 2021. Bringing Full-featured Mobile Phone Interaction into Virtual Reality. *Computers & Graphics* 97: 42–53. https://doi.org/10.1016/j.cag.2021.04.004
9. Shahin Basiratzadeh, Edward D. Lemaire, Masoud Dorrikhteh, and Natalie Baddour. 2019. Fiducial marker approach for biomechanical smartphone-based measurements. *BioSMART 2019 - Proceedings: 3rd International Conference on Bio-Engineering for Smart Technologies*: 25–28. https://doi.org/10.1109/BIOSMART.2019.8734237
10. Joanna Bergstrom-Lehtovirta and Antti Oulasvirta. 2014. Modeling the functional area of the thumb on mobile touchscreen surfaces. *Conference on Human Factors in Computing Systems - Proceedings*: 1991–2000. https://doi.org/10.1145/2556288.2557354
11. Bobby Bodenheimer, Sarah Creem-Regehr, Jeanine Stefanucci, Elena Shemetova, and William B. Thompson. 2017. Prism aftereffects for throwing with a self-avatar in an immersive virtual environment. *Proceedings - IEEE Virtual Reality* 0: 141–147. https://doi.org/10.1109/VR.2017.7892241

12. Mark Bolas, James Iliff, Perry Hoberman, Nate Burba, Thai Phan, Ian McDowall, Palmer Luckey, and David M. Krum. 2013. Open virtual reality. *Proceedings - IEEE Virtual Reality*: 183–184. https://doi.org/10.1109/VR.2013.6549423

13. Jean Botev, Joe Mayer, and Steffen Rothkugel. 2019. Immersive mixed reality object interaction for collaborative context-aware mobile training and exploration. *Proceedings of the 11th ACM Workshop on Immersive Mixed and Virtual Environment Systems, MMVE 2019*: 4–9. https://doi.org/10.1145/3304113.3326117

14. David Brickler, Robert Teather, Andrew Duchowski, and Sabarish Babu. 2020. A Fitts' Law Evaluation of Visuo-haptic Fidelity and Sensory Mismatch on User Performance in a Near-field Disc Transfer Task in Virtual Reality. *ACM Transactions on Applied Perception* 17: 1–20. https://doi.org/10.1145/3419986

15. Géry Casiez and Nicolas Roussel. 2011. No more bricolage!: Methods and tools to characterize, replicate and compare pointing transfer functions. *UIST'11 - Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*: 603–614. https://doi.org/10.1145/2047196.2047276

16. Marc Cavazza, Jean-Luc Lugrin, Sean Crooks, Alok Nandi, Mark Palmer, and Marc Le Renard. 2005. Causality and Virtual Reality Art Augmented and Virtual Reality -Virtual Reality for Art and Entertainment INTRODUCTION AND RATIONALE. 1: 4–12.

17. Marc Cavazza, Jean Luc Lugrin, Simon Hartley, Paolo Libardi, Matthew J. Barnes, Mikael Le Bras, Marc Le Renard, Louis Bec, and Alok Nandi. 2004. New ways of worldmaking: The alterne platform for VR art. *ACM Multimedia 2004 -*

proceedings of the 12th ACM International Conference on Multimedia, Figure 1: 80–87.

18. Yu Chien Chen. 2006. A study of comparing the use of augmented reality and physical models in chemistry education. *Proceedings - VRCIA 2006: ACM International Conference on Virtual Reality Continuum and its Applications* 1, June: 369–372. https://doi.org/10.1145/1128923.1128990
19. Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D. Wilson. 2017. Sparse Haptic Proxy. 3718–3728. https://doi.org/10.1145/3025453.3025753
20. Sungmin Cho, Won-Seok Kim, Seo Hyun Park, Jihong Park, and Nam-Jong Paik. 2020. Virtual Prism Adaptation Therapy: Protocol for Validation in Healthy Adults. *Journal of visualized experiments : JoVE*, 156. https://doi.org/10.3791/60639
21. Jonathan Deber, Ricardo Jota, Clifton Forlines, and Daniel Wigdor. 2015. How much faster is fast enough? User perception of latency & latency improvements in direct and indirect touch. *Conference on Human Factors in Computing Systems - Proceedings* 2015-April, 1: 1827–1836. https://doi.org/10.1145/2702123.2702300
22. Seyed Amir Ahmad Didehkhorshid and Robert J. Teather. 2020. Selection performance using a scaled virtual stylus cursor in VR. *Proceedings - Graphics Interface* 2020-May.
23. Sarah A. Douglas, Arthur E. Kirkpatrick, and I. Scott MacKenzie. 1999. Testing pointing device performance and user assessment with the IS0 9241, Part 9 standard. *Conference on Human Factors in Computing Systems - Proceedings*,

May: 215–222. https://doi.org/10.1145/302979.303042

24. Juan Fernandez-Ruiz and Rosalinda Díaz. 1999. Prism Adaptation and Aftereffect: Specifying the Properties of a Procedural Memory System. *Learning & memory (Cold Spring Harbor, N.Y.)* 6: 47–53. https://doi.org/10.1101/lm.6.1.47

25. Tiare Feuchtner and Jörg Müller. 2018. Ownershift. 31–43. https://doi.org/10.1145/3242587.3242594

26. P M Fitts. 1992. The information capacity of the human motor system in controlling the amplitude of movement. 1954. *Journal of experimental psychology. General* 121, 3: 262–269. https://doi.org/10.1037//0096-3445.121.3.262

27. Clifton Forlines. 2007. Direct-Touch vs . Mouse Input for Tabletop Displays. 647–656.

28. Clifton Forlines, Mitsubishi Electric, and Ravin Balakrishnan. 2008. Evaluating Tactile Feedback and Direct vs . Indirect Stylus Input in Pointing and Crossing Selection Tasks.

29. Anton Franzluebbers and Kyle Johnsen. 2018. Performance benefits of high-fidelity passive haptic feedback in virtual reality training. *SUI 2018 - Proceedings of the Symposium on Spatial User Interaction*: 16–24. https://doi.org/10.1145/3267782.3267790

30. Mareike Frevert and David S. Di Fuccia. 2019. Virtual reality as a means of teaching contemporary chemistry. *ACM International Conference Proceeding Series*: 34–38. https://doi.org/10.1145/3369199.3369218

31. Akira Fuji, Makoto Fujimura, and Toshio Higashi. 2018. Virtual Environment of

Prism Adaptation for Unilateral Spatial Neglect. *2018 IEEE 7th Global Conference on Consumer Electronics, GCCE 2018*: 81–82. https://doi.org/10.1109/GCCE.2018.8574783

32. Makoto Fujimura, Kazuya Nakatomi, Akira Fujii, and Toshio Higashi. 2019. Problem of pointing target in virtual environment for prism adaptation. *2019 IEEE 1st Global Conference on Life Sciences and Technologies, LifeTech 2019*: 8–9. https://doi.org/10.1109/LifeTech.2019.8884066

33. Stephan Joachim Garbin, Yiru Shen, Immo Schuetz, Robert Cavin, Gregory Hughes, Oleg Komogortsev, and Sachin S. Talathi. 2020. Dataset for eye tracking on a virtual reality platform. *Eye Tracking Research and Applications Symposium (ETRA)*. https://doi.org/10.1145/3379155.3391317

34. Sascha Gebhardt, Sebastian Pick, Thomas Oster, Bernd Hentschel, and Torsten Kuhlen. 2014. An evaluation of a smart-phone-based menu system for immersive virtual environments. *IEEE Symposium on 3D User Interfaces 2014, 3DUI 2014 - Proceedings*: 31–34. https://doi.org/10.1109/3DUI.2014.6798837

35. Joris Groen and Peter J Werkhoven. 1998. Visuomotor Adaptation to Virtual Hand Position in Interactive Virtual Environments. *Presence* 7, 5: 429–446. https://doi.org/10.1162/105474698565839

36. Dustin T. Han, Mohamed Suhail, and Eric D. Ragan. 2018. Evaluating remapped physical reach for hand interactions with passive haptics in virtual reality. *IEEE Transactions on Visualization and Computer Graphics* 24, 4: 1467–1476. https://doi.org/10.1109/TVCG.2018.2794659

37. Shangchen Han, Beibei Liu, Randi Cabezas, Christopher D. Twigg, Peizhao

Zhang, Jeff Petkau, Tsz-Ho Yu, Chun-Jung Tai, Muzaffer Akbay, Zheng Wang, Asaf Nitzan, Gang Dong, Yuting Ye, Lingling Tao, Chengde Wan, and Robert Wang. 2020. MEgATrack. *ACM Transactions on Graphics* 39, 4. https://doi.org/10.1145/3386569.3392452

38. John Paulin Hansen, Vijay Rajanna, I. Scott MacKenzie, and Per Bækgaard. 2018. A Fitts' law study of click and dwell interaction by gaze, head and mouse with a head-mounted display. *Proceedings - COGAIN 2018: Communication by Gaze Interaction*: 2–6. https://doi.org/10.1145/3206343.3206344

39. Samory Houzangbe, Geoffrey Gorisse, Olivier Christmann, and Simon Richir. 2018. Integrability and reliability of smart wearables in virtual reality experiences: A subjective review. *ACM International Conference Proceeding Series*. https://doi.org/10.1145/3234253.3234305

40. Samat Imamov, Daniel Monzel, and Wallace S Lages. 2020. Where to display ? How Interface Position Affects Comfort and Task Switching Time on Glanceable Interfaces. 851–858. https://doi.org/10.1109/VR46266.2020.00110

41. Johann Habakuk Israel, Oliver Belaifa, Adrienne Gispen, and Rainer Stark. 2011. An object-centric interaction framework for tangible interfaces in virtual environments. *Proceedings of the 5th International Conference on Tangible Embedded and Embodied Interaction, TEI'11*: 325–332. https://doi.org/10.1145/1935701.1935777

42. Jun Jia, Yue Qi, and Qing Zuo. 2010. An extended marker-based tracking system for Augmented Reality. *Proceedings - 2010 2nd International Conference on Modeling, Simulation, and Visualization Methods, WMSVM 2010*: 94–97.

https://doi.org/10.1109/WMSVM.2010.52

43. Nicholas Katzakis, Robert J. Teather, Kiyoshi Kiyokawa, and Haruo Takemura. 2015. INSPECT: extending plane-casting for 6-DOF control. *Human-centric Computing and Information Sciences* 5, 1. https://doi.org/10.1186/s13673-015-0037-y

44. Luv Kohli. 2010. Redirected touching: Warping space to remap passive haptics. *3DUI 2010 - IEEE Symposium on 3D User Interfaces 2010, Proceedings*: 129–130. https://doi.org/10.1109/3DUI.2010.5444703

45. Luv Kohli, Mary C. Whitton, and Frederick P. Brooks. 2012. Redirected touching: The effect of warping space on task performance. *IEEE Symposium on 3D User Interfaces 2012, 3DUI 2012 - Proceedings*: 105–112. https://doi.org/10.1109/3DUI.2012.6184193

46. Luv Kohli, Mary C. Whitton, and Frederick P. Brooks. 2013. Redirected Touching: Training and adaptation in warped virtual spaces. *IEEE Symposium on 3D User Interface 2013, 3DUI 2013 - Proceedings*: 79–86. https://doi.org/10.1109/3DUI.2013.6550201

47. Alena Kovarova and Maros Urbancok. 2014. Can virtual reality be better controlled by a smart phone than by a mouse and a keyboard? *ACM International Conference Proceeding Series* 883: 317–324. https://doi.org/10.1145/2659532.2659608

48. Kapil Kumar, Arindam Mondal, and Gaurav Gupta. 2019. Watch360: A Device to Enable and Detect Tilt, Translation and Rotation of a Watch Bezel. *2019 16th IEEE Annual Consumer Communications and Networking Conference, CCNC*

2019. https://doi.org/10.1109/CCNC.2019.8651875

49. Sungkil Lee, Gerard Jounghyun Kim, and Seungmoon Choi. 2007. Real-time tracking of visually attended objects in interactive virtual environments. *Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST* 1, 212: 29–38. https://doi.org/10.1145/1315184.1315187

50. Andrea Li. 2008. Experiencing visuo-motor plasticity by prism adaptation in a classroom setting. *Journal of undergraduate neuroscience education : JUNE : a publication of FUN, Faculty for Undergraduate Neuroscience* 7, 1: A13–A18. Retrieved from https://pubmed.ncbi.nlm.nih.gov/23494088

51. Hai Ning Liang, Yuwei Shi, Feiyu Lu, Jizhou Yang, and Konstantinos Papangelis. 2016. VRM controller: An input device for navigation activities in virtual reality environments. *Proceedings - VRCAI 2016: 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry* 1: 455–460. https://doi.org/10.1145/3013971.3014005

52. Peter Lightbody, Tomáš Krajník, and Marc Hanheide. 2017. An efficient visual fiducial localisation system. *ACM SIGAPP Applied Computing Review* 17, 3: 28–37. https://doi.org/10.1145/3161534.3161537

53. Kent Lyons. 2016. 2D input for virtual reality enclosures with magnetic field sensing. *International Symposium on Wearable Computers, Digest of Papers* 12-16-Sept: 176–183. https://doi.org/10.1145/2971763.2971787

54. Kevin Mack. 2017. Blortasia : A Virtual Reality Art Experience. *SIGGRAPH '17 VR Village*: 2.

55. I. Scott MacKenzie and Poika Isokoski. 2008. Fitts' throughput and the speed-

accuracy tradeoff. *Conference on Human Factors in Computing Systems - Proceedings*: 1633–1636. https://doi.org/10.1145/1357054.1357308

56. I Scott MacKenzie. 1992. Fitts' Law as a Research and Design Tool in Human-Computer Interaction. *Hum.-Comput. Interact.* 7, 1: 91–139. https://doi.org/10.1207/s15327051hci0701_3

57. I Scott MacKenzie. 2013. Chapter 3 - Interaction Elements. In I Scott B T - Human-computer Interaction MacKenzie (ed.). Morgan Kaufmann, Boston, 71–120. https://doi.org/https://doi.org/10.1016/B978-0-12-405865-1.00003-0

58. Stefan Marks, David White, and Manpreet Singh. 2017. Getting up your nose: a virtual reality education tool for nasal cavity anatomy. *SIGGRAPH Asia 2017 Symposium on Education, SA 2017*. https://doi.org/10.1145/3134368.3139218

59. Anne Collins Mclaughlin, Wendy A Rogers, and Arthur D Fisk. 2009. Using Direct and Indirect Input Devices : Attention Demands and Age-Related Differences. 16, 1: 1–15. https://doi.org/10.1145/1502800.1502802

60. Tim Menzner, Travis Gesslein, Alexander Otte, and Jens Grubert. 2020. Above Surface Interaction for Multiscale Navigation in Mobile Virtual Reality. *Proceedings - 2020 IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2020*: 372–381. https://doi.org/10.1109/VR46266.2020.1581107639032

61. Mark R. Mine, Frederick P. Brooks, and Carlo H. Sequin. 1997. Moving objects in space: Exploiting proprioception in virtual-environment interaction. *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques, SIGGRAPH 1997*: 19–26. https://doi.org/10.1145/258734.258747

62. J. Logan Olson, David M. Krum, Evan A. Suma, and Mark Bolas. 2011. A design

for a smartphone-based head mounted display. *Proceedings - IEEE Virtual Reality*: 233–234. https://doi.org/10.1109/VR.2011.5759484

63. Paul M. Fitts. 1954. the Information Capacity of the Human Motor System in Controlling the Amplitude of Movement. *Journal of Experimental Psychology* 47, 6: 381–391. Retrieved from http://www2.psychology.uiowa.edu/faculty/mordkoff/InfoProc/pdfs/Fitts 1954.pdf

64. W PEDDIE. 1925. Helmholtz's Treatise on Physiological Optics. *Nature* 116, 2907: 88–89. https://doi.org/10.1038/116088a0

65. Krzysztof Pietroszek and Chao Cheng Lin. 2019. UniVResity: Face-to-face class participation for remote students using virtual reality. *Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST*. https://doi.org/10.1145/3359996.3364730

66. M H Pirenne. 1967. *Vision and the Eye*. Chapman \& Hall. Retrieved from https://books.google.com.ua/books?id=OuVqAAAAMAAJ

67. Johanna Pirker, Andreas Dengel, Michael Holly, and Saeed Safikhani. 2020. Virtual Reality in Computer Science Education: A Systematic Review. *Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST*. https://doi.org/10.1145/3385956.3418947

68. Ivan Poupyrev, Mark Billinghurst, Suzanne Weghorst, and Tadao Ichikawa. 1996. The go-go interaction technique. 79–80. https://doi.org/10.1145/237091.237102

69. Gerhard Reitmayr and Dieter Schmalstieg. 2001. An open software architecture for virtual reality interaction. *ACM Symposium on Virtual Reality Software and Technology, Proceedings, VRST*: 47–54. https://doi.org/10.1145/505008.505018

70. S. Wellek. 2010. *Testing Statistical Hypotheses of Equivalence and Noninferiority*.

71. Boris Smus and Christopher Riederer. 2015. Magnetic input for mobile virtual reality. *ISWC 2015 - Proceedings of the 2015 ACM International Symposium on Wearable Computers*: 43–44. https://doi.org/10.1145/2802083.2808395

72. R. William Soukoreff and I. Scott MacKenzie. 2004. Towards a standard for pointing device evaluation, perspectives on 27 years of Fitts' law research in HCI. *International Journal of Human Computer Studies* 61, 6: 751–789. https://doi.org/10.1016/j.ijhcs.2004.09.001

73. David W. Sprague, Barry A. Po, and Kellogg S. Booth. 2006. The importance of accurate VR head registration on skilled motor performance. *Proceedings - Graphics Interface* 2006: 131–137.

74. Zhibo Sun, Ashish Dhital, Nattaya Areejitkasem, Neera Pradhan, and Amy Banic. 2014. Effects on Performance of Analytical Tools for Visually Demanding Tasks through Direct and Indirect Touch Interaction in an Immersive Visualization. https://doi.org/10.1109/ICVRV.2014.73

75. R J Teather, D Natapov, and M Jenkin. 2010. Evaluating haptic feedback in virtual environments using ISO 9241–9. In *2010 IEEE Virtual Reality Conference (VR)*, 307–308. https://doi.org/10.1109/VR.2010.5444753

76. Robert J Teather, Robert S Allison, and Wolfgang Stuerzlinger. 2009. Evaluating Visual / Motor Co-location in Fish-Tank Virtual Reality.

77. Robert J Teather, Andriy Pavlovych, Wolfgang Stuerzlinger, and I Scott MacKenzie. 2009. Effects of Tracking Technology, Latency, and Spatial Jitter on Object Movement. In *Proceedings of the 2009 IEEE Symposium on 3D User*

Interfaces (3DUI '09), 43–50. https://doi.org/10.1109/3DUI.2009.4811204

78. Robert Teather and I MacKenzie. 2020. Position vs. Velocity Control for Tilt-Based Interaction. . 51–58. https://doi.org/10.1201/9781003059325-7

79. Robert Teather and Wolfgang Stuerzlinger. 2011. *Pointing at 3D targets in a stereo head-tracked virtual environment*. https://doi.org/10.1109/3DUI.2011.5759222

80. Philipp Tiefenbacher, Steven Wichert, Daniel Merget, and Gerhard Rigoll. 2014. Impact of coordinate systems on 3D manipulations in mobile augmented reality. *ICMI 2014 - Proceedings of the 2014 International Conference on Multimodal Interaction*: 435–438. https://doi.org/10.1145/2663204.2663234

81. Xin Wang and Xiuyue Wang. 2018. Virtual Reality training system for surgical anatomy. *ACM International Conference Proceeding Series*, 201604054: 30–34. https://doi.org/10.1145/3293663.3293670

82. Colin Ware and Roland Arsenault. 2004. Frames of reference in virtual object rotation. *Proceedings - 1st Symposium on Applied Perception in Graphics and Visualization, APGV 2004* 1, 212: 135–142. https://doi.org/10.1145/1012551.1012576

83. Pingbo Yin and Shigeru Kitazawa. 2001. Long-lasting aftereffects of prism adaptation in the monkey. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale* 141: 250–253. https://doi.org/10.1007/s002210100892

84. Neng Hao Yu, Da Yuan Huang, Jia Jyun Hsu, and Yi Ping Hung. 2013. Rapid selection of hard-to-access targets by thumb on mobile touch-screens. *MobileHCI*

2013 - Proceedings of the 15th International Conference on Human-Computer Interaction with Mobile Devices and Services: 400–403. https://doi.org/10.1145/2493190.2493202

85. André Zenner, Hannah Maria Kriegler, and Antonio Krüger. 2021. HaRT - The Virtual Reality Hand Redirection Toolkit. *Conference on Human Factors in Computing Systems - Proceedings*. https://doi.org/10.1145/3411763.3451814

86. Shumin Zhai. 1993. Investigation of Feel for 6DOF Inputs: Isometric and Elastic Rate Control for Manipulation in 3D Environments. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 37, 4: 323–327. https://doi.org/10.1177/154193129303700415

87. Li Zhang, Huidong Bai, Mark Billinghurst, and Weiping He. 2020. Is This My Phone? Operating a Physical Smartphone in Virtual Reality. *SIGGRAPH Asia 2020 XR, SA 2020*, Figure 1: 1–2. https://doi.org/10.1145/3415256.3421499

88. Lu Zhao, Yue Liu, Dejiang Ye, Zhuoluo Ma, and Weitao Song. 2020. Implementation and Evaluation of Touch-based Interaction Using Electrovibration Haptic Feedback in Virtual Environments. *Proceedings - 2020 IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2020*: 239–247. https://doi.org/10.1109/VR46266.2020.1581066900344