Integrating Wearable and Haptic Devices for Enhanced Input and Interaction in Virtual Reality

by

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University of California, Merced

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Abstract

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As the affordability and availability of virtual reality hardware increases, its adoption is also rapidly growing. Yet, input and interaction in virtual reality remains a significant challenge. Existing interaction techniques often lack intuitiveness, precision, and the spatial feedback users are accustomed to in the real world. They can also be cumbersome and lack mobility, further limiting usability and immersion. Furthermore, virtual reality lacks effective and efficient methods for text input. These limitations restrict the widespread adoption of virtual reality, primarily confining it to entertainment and training simulations. Furthermore, since virtual reality is still in its infancy, there is a lack of design guidelines to help designers and developers, leading to decisions driven primarily by intuition. This dissertation investigates the use of wearable and haptic technologies to overcome these limitations and create more intuitive and efficient virtual reality experiences.

First, addressing the challenges of text input in virtual reality, this dissertation begins with an investigation into the impact of key shape and dimension on text entry performance and preference. The aim is to contribute to the standardization of design practices in virtual reality through empirical data. We compare three common key shapes: hexagonal, round, square, in both two-dimension (2D) and three-dimension (3D). The results indicate that the 3D square keys provide superior performance in terms of accuracy and user preference. This suggests that replicating familiar real-world elements can significantly enhance usability, especially when a technology is in its infancy. Publication # 5.

Second, building on these findings, we investigate mid-air text input, which is a common scenario in virtual reality environments. To address the lack of spatial feedback resulting from the absence of a physical surface, we utilize an ultrasonic haptic feedback device. In addition to incorporating the design insights from the first study, we develop three different ultrasonic haptic feedback methods: feedback only on keypress, on both touch and keypress, and gradual feedback that increases in intensity as users push down a key. A pilot study revealed that the touch & press feedback performed significantly better, both quantitatively and qualitatively. We therefore compare a mid-air keyboard with and without touch & press feedback in a user study. Results revealed that haptic feedback improves entry speed by 16% and reduces the error rate by 26%. In addition, most participants feel that it enhances presence and spatial awareness in the virtual world by maintaining a higher

consistency with the real world and significantly reduces mental demand, effort, and frustration. Publication # 2.

Third, extending upon mid-air interaction, we investigate the effectiveness of different selection gestures augmented with ultrasonic haptic feedback. We compare four commonly used mid-air target selection methods: Push, Tap, Dwell, Pinch, with two types of ultrasonic haptic feedback: feedback upon selection only, and feedback on both hover and selection, in a Fitts' law experiment. Results reveal that Tap is the fastest, the most accurate, and one of the least physically and cognitively demanding selection methods. Pinch is relatively fast but error-prone and physically and cognitively demanding. Dwell is slowest by design, yet the most accurate and the least physically and cognitively demanding. Both haptic feedback methods improve selection performance by increasing users' spatial awareness. Participants perceive the selection methods as faster, more accurate, and more physically and cognitively comfortable with the haptic feedback methods. Based on these findings, we provide guidelines for choosing optimal mid-air selection gestures considering technological limitations and task requirements. Publication # 3.

Fourth, we further extend selection gestures and input methods in virtual reality by developing a custom wearable device that does not occupy the hands, thereby leaving them free for other tasks. We introduce a novel finger-worn device for gesture typing in virtual reality, termed the "digital thimble", which users wear on their index finger. This thimble utilizes an optical sensor to track finger movement and a pressure sensor to detect touch and contact force. We also introduce Shapeshifter, a technique that enables text entry in virtual reality through gestures and varying contact force on any opaque, diffusely reflective surface, including the human body. A week-long in-the-wild pilot study shows that Shapeshifter yields, on average, 11 words per minute (wpm) on flat surfaces (e.g., a desk), 9 wpm on the lap when sitting, and 8 wpm on the palm and back of the hand while standing in text composition tasks. In a simulation study, Shapeshifter achieves 27 wpm for text transcription tasks, outperforming current gesture typing techniques in virtual reality. Publication # 4.

Finally, we extend the functionality of the digital thimble further and explore its usability in the context of target selection, sorting, and teleportation. We start with a Fitts' law study that compares the digital thimble with a commercial wearable mouse (previously unexplored in virtual reality contexts) and a traditional controller, using two selection methods: press and touch-release. A second user study investigates the devices for sorting and teleportation tasks. While the finger mouse demonstrated superior throughput and task completion speed, the digital thimble showed greater accuracy and precision. Participants also favored the digital thimble for its enhanced comfort, convenience, and overall user-friendliness. These findings highlight the digital thimble's potential as a versatile and comfortable input device for virtual reality applications, offering valuable advantages over traditional alternatives. Publication # 1 (under review).

This dissertation makes significant progress in addressing the core challenges associated with input and interaction in virtual reality, setting the foundation for more intuitive and natural interactions within virtual environments. The insights gained have the potential to enhance the accessibility and applicability of virtual reality across a broad spectrum of fields, such as education, training, collaboration, and healthcare, thereby broadening its impact and utility.

Publications

My Ph.D. research yielded five refereed publications, with a sixth currently being prepared for publication. This dissertation incorporates four of these publications, including the one under review. The sixth publication, listed below, is not included in this dissertation. Additionally, during the course of my Ph.D., I developed a haptic glove prototype and an eye-based gesture typing system for virtual reality applications, which are also not included.

1. Tafadzwa Joseph Dube, Ahmed Sabbir Arif. 2024. Design and Evaluation of a Finger Wearable for Freehand Input and Interaction in Virtual Reality. **Currently being prepared for publication**.
2. Tafadzwa Joseph Dube, Ahmed Sabbir Arif. 2023. Ultrasonic Keyboard: A Mid-Air Virtual Qwerty with Ultrasonic Feedback for Virtual Reality. In *the 17th International Conference on Tangible, Embedded, and Embodied Interaction* (TEI 2023). ACM, New York, NY, USA, 8 pages.
3. Tafadzwa Joseph Dube, Yuan Ren, Hannah Limerick, Scott MacKenzie, Ahmed Sabbir Arif. 2022. Push, Tap, Dwell, and Pinch: Evaluation of Four Mid-Air Selection Methods Augmented with Ultrasonic Haptic Feedback. In *the Proceedings of the 2022 ACM Interactive Surfaces and Spaces Conference* (ISS 2022). ACM, New York, NY, USA, 19 pages. **Best Paper Award**.
4. Tafadzwa Joseph Dube, Kevin Johnson, Ahmed Sabbir Arif. 2022. Shapeshifter: Gesture Typing in Virtual Reality with a Force-based Digital Thimble. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems* (CHI EA 2022). ACM, New York, NY, USA, Article 230, 1–9.
5. Tafadzwa Joseph Dube, Ahmed Sabbir Arif. 2020. Impact of Key Shape and Dimension on Text Entry in Virtual Reality. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (CHI EA 2020). ACM, New York, NY, USA, 1–10.
6. Tafadzwa Joseph Dube, Ahmed Sabbir Arif. 2019. *Text Entry in Virtual Reality: A Comprehensive Review of the Literature*. In Kurosu M. (Eds.), Human-Computer Interaction. Recognition and Interaction Technologies (HCII '19), Lecture Notes in Computer Science, 11567. Springer, Cham, Switzerland, 419-437.

To my parents.

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Acknowledgments

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This dissertation is a reflection of the collective support and encouragement of each individual mentioned, including the insightful reviewers, and many others not mentioned by name who have contributed in countless ways. I am profoundly grateful to all of you for your role in this journey.

Chapter 1

Introduction

The use of virtual reality (VR) is rapidly expanding, finding applications in the health, manufacturing, military, education, and entertainment sectors. This surge is accelerated by the increasing affordability and availability of VR hardware. Major companies such as HTC, Google, Apple, Amazon, Microsoft, Sony, and Samsung are actively developing their VR head-mounted displays (HMDs), which are leading to reduced consumer costs and improvements in the form factor of the devices. As a result, today's HMDs are smaller and more stylish, making them appealing to a broader audience. Recent surveys have shown a significant increase in VR users, with expectations of continued growth in the near future. For example, Statista reported that from 2020 to 2022, the number of VR users more than doubled, reaching approximately 60 million. This upward trend is expected to persist in the coming years (Fig. 1.1). Economically, the size of the global market for virtual reality is expected to increase rapidly, from $12 billion in 2022 to more than $22 billion by 2025 [203]. In 2017, Mark Zuckerberg, CEO of Meta, announced that his company plans to invest $3 billion in virtual reality technologies over the next decade to make it more accessible [62]. The emergence of the Metaverse [199] is also likely to increase the growth of VR technology.

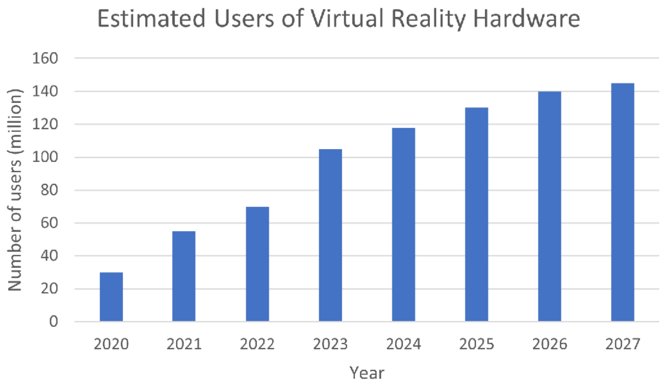

Figure 1.1: The estimated number of virtual reality users globally between 2020 and 2027. Between 2020 and 2022 the number of virtual reality users more than doubled. Source: Statista [203].

Despite this progress, input and interaction within virtual reality remain significant challenges. HMDs, by their nature, obscure the user's view of the physical world (Fig. 1.2), making it difficult to use traditional input devices. Current VR input methods often suffer from being error-prone, cumbersome, lacking in spatial feedback, or simply difficult to master. Although ongoing research is directed at addressing these issues, a considerable gap still exists in developing intuitive, natural, and seamless interaction methods for VR environments. Virtual reality has always had the promise of immersing users in entirely fabricated worlds. Early versions concentrated primarily on visual and auditory elements, but recent developments in wearable and haptic technologies are transforming interactions within these digital environments. Haptic devices, especially, add a crucial tactile dimension to VR, significantly enhancing the realism and engagement of the user experience. This dissertation will explore both current and emerging input methods using wearable and haptic devices within VR settings, examine their effects, and suggest future pathways to improve interaction and immersion.

(a) User using a controller

(b) User using mid-air gestures

Figure 1.2: (a) A virtual reality user using a controller and (b) a virtual reality user using mid-air gestures.

Handheld controllers remain the predominant interface in VR settings, as they are standard accessories for most VR headsets. These devices enable versatile interactions with virtual environments through physical buttons and gesture recognition (Fig. 1.2a). Users can manipulate objects, navigate menus, and teleport using these controllers. Their design, often similar to video game controllers, makes them particularly intuitive for gamers. Despite these advantages, handheld controllers also present significant limitations. For example, its use occupies hands, restricting the user's ability to perform other tasks within the VR space [231]. This can lead to a diminished sense of presence and immersion. In addition, locating controllers while wearing a VR headset can be cumbersome, often requiring users to remove their headsets and interrupt their experience. Prolonged use can also result in user fatigue and discomfort. As VR technology continues to evolve, there is a pressing need for more seamless and intuitive interaction methods that emphasize natural gestures and minimize user burden. With advances in hand-tracking technology, the prospects for more fluid and naturalistic VR interactions are rapidly expanding.

The integration of hand-tracking technology into VR has transformed user interaction, enabling mid-air gestures that mirror real-world actions. This advancement is increasingly common in modern VR headsets, such as the Oculus Quest, Pico Neo, and HTC Vive 2. Mid-air interaction is valued for its naturalness and intuitiveness, allowing users to engage with virtual environments in ways that feel familiar and instinctive. Such interaction is supported by substantial literature that emphasizes its effectiveness in improving user engagement and the sense of immersion within virtual spaces [83, 223, 27, 117, 67]. Despite its advantages, mid-air interaction faces significant challenges, notably the lack of tactile feedback. This absence of physical contact points means that users often lack spatial awareness, making gestures less intuitive and more cognitively demanding [36, 10]. This can adversely affect the speed, accuracy, and overall comfort of interactions.

Addressing this gap requires innovative solutions to provide effective haptic feedback, enhancing the realism of virtual interactions. Although wearable devices such as haptic gloves offer one approach, they can be cumbersome and disrupt the natural flow of movements [20]. Therefore, this dissertation explores non-intrusive alternatives, particularly ultrasonic haptic feedback, which promise to deliver tactile sensations without the encumbrance of physical devices. Focusing on ultrasonic haptic feedback, this research aims to assess its impact on text entry and common mid-air gestures in VR. By investigating this technology, we aim to contribute to the development of more intuitive and immersive VR experiences.

The challenges of text entry in VR highlight critical areas for improvement in VR technology, especially as it aims to transition from predominantly entertainment and training applications to more comprehensive productivity tools. Text input within VR remains slow, cumbersome, and error-prone, significantly hindering its mainstream adoption for productivity purposes [54, 70, 181, 21]. The absence of standardized guidelines or best practices for VR text entry exacerbates these issues, leading to a variety of inconsistent keyboard layouts and input methods that complicate the optimization process.

The surge in remote work catalyzed by the COVID-19 pandemic and the subsequent rise of virtual office applications such as Meta's Horizon Workrooms and Rummi highlight the growing need for effective VR text entry solutions [58, 51]. This need extends beyond office applications to include other VR contexts such as password entry, collaborative projects, training environments, and social networking [152, 163], emphasizing the need for rapid and accurate text input to unlock VR's full potential.

To address these challenges, our research explores innovative input and interaction solutions, specifically focusing on haptic and wearable technologies. Haptic devices, particularly through the use of ultrasonic haptic feedback, offer promising avenues for enhancing user interaction by simulating physical sensations directly in mid-air. This non-intrusive approach allows for more natural hand-tracking interactions and aims to improve the precision and ease of text entry and other common VR gestures without the physical burden of gloves or other handheld devices.

In addition, wearable devices offer a compelling alternative. Designed to be worn directly on the body (e.g., on wrists, fingers, or heads), these devices seamlessly integrate into the user experience, maintaining constant readiness, and addressing the discoverability issues associated with handheld controllers. Wearables such as rings and bracelets offer refined control and enhance the feeling of presence within the virtual environment. However, the complexity and novel interaction techniques required by some wearables pose significant barriers to adoption, characterized by steep learning curves that may deter users [75, 132].

Our work proposes the development of wearable solutions that prioritize ease of use. Using familiar gestures and minimizing the need for new learning, we aim to facilitate a smoother transition for users to VR environments, improving both their effectiveness and comfort. This approach not only strives to improve VR interactions, but also supports the broader goal of making VR a viable tool for a wide range of applications, from productivity to social connectivity.

1.1 Contribution

The contribution of this work is five-fold. First (§2), we explored how key shape and dimension affect virtual reality text input, comparing hexagonal, round, and square shapes in 3D and 2D on a virtual desk. The findings offer guidelines for virtual keyboard development and suggest that 3D square keys, mirroring the real world, perform best, marking a step towards standardized VR design based on empirical data. Second (§3), addressing mid-air text entry, a common VR scenario, we introduce an ultrasonic haptic keyboard to provide spatial feedback, informed by the initial study. We examined three types of ultrasonic feedback: on press, touch and press, and gradual increase on press. Our findings highlight that ultrasonic haptic feedback significantly enhances text entry by improving spatial awareness. Third (§4), extending to vertical interactions common in VR and real-world settings such as kiosks, we evaluated four mid-air gestures (Tap, Push, Pinch, Dwell) with and without ultrasonic haptic feedback for selection. The tap was the most efficient, but all gestures suited different user needs. Haptic feedback was shown to boost performance by improving spatial awareness, with implications for various interaction interfaces. Fourth (§5), using existing technology led us to develop a novel force-based digital thimble for gesture typing on any surface, including the body. Through practical and simulated studies, this device outperformed existing methods, demonstrating its efficacy. Lastly (§6), improving the design of the digital thimble, we assessed its utility for other VR interactions through user studies, comparing it with a commercial finger mouse and a standard VR controller. Although the finger mouse excelled in speed, the digital thimble was more accurate and preferred for its comfort and ease of use, demonstrating its potential as an effective VR input device.

Chapter 2

Virtual Key Shape and Dimension

In this Chapter, we attempt to develop guidelines for designing keyboards for text input in virtual reality. Most works in this domain explore different tracking mechanisms and develop novel input techniques and technologies without much consideration for how the design of the keys (the shape, size, dimension, color of the keys, etc.) affects text entry performance. This has resulted in the emergence of virtual keyboards with a range of key designs (a quick search on the Unity Asset Store[1] can attest to this). This lack of understanding can slow down progress in optimizing text entry in virtual reality. To our knowledge, no work has explored whether key shape and dimension affect text entry performance and user experience in the context of virtual reality. To address this, we conducted a comparative study to evaluate the performance of six different key designs (3 shapes $\times$ 2 dimensions) on text entry performance and user experience in virtual reality. We identified the commonly used shapes (square, round, hexagonal) and dimensions (2D and 3D) in virtual reality from the literature as outlined in Table 2.1.

In virtual reality, there is a lack of consistent design principles for virtual keyboards, despite text entry being a fundamental task in many virtual reality interactions. We found that developers and designers take the liberty to design different virtual reality keyboards (e.g., different shapes, colors, and keys). However, in the physical world, there is some form of a standard of the physical Qwerty that has helped to optimize text entry [26, 154, 35]. In addition, various studies investigated soft keyboards for touch screens to identify ways to standardize and optimize their design [41, 42, 135, 242]. Research has also shown that even seemingly minor details, like background design, can influence text input [234]. Thus, understanding the specific impacts of various factors within virtual reality will empower designers to make informed choices that enhance text entry performance. However, since virtual reality is in its infancy, most works have focused on developing novel text input methods with little work focusing on the impacts of basic aspects of text entry. The influence of specific key characteristics (shape, size, dimensionality) remains largely underexplored. Existing guidelines for physical and soft keyboards [155, 185, 234, 38, 109, 38] offer limited help for virtual reality contexts, as the absence of tactile feedback and unique hand-tracking affordances significantly alter the user experience. This highlights a clear need for systematic research. Our work directly targets this gap, aiming to provide a foundation for design choices that optimize both text entry performance and overall user experience within virtual reality environments.

For the remainder of this Chapter, we begin with a review of related work. Following this, we

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[1] Unity Asset Store https://assetstore.unity.com

provide a detailed description of our experimental methodology, including the apparatus, participant demographics, and study design. Subsequently, we present and discuss the results of our study. Finally, the Chapter concludes with a summary of key findings.

2.1 Related Work

Recently, researchers have been tackling the text entry challenge in virtual reality. Many enabled text entry with physical Qwerty keyboards by using external sensors to track the keyboard and the hands, then displaying their virtual representations in the virtual world [70, 181, 19, 111, 141, 86, 166, 115, 144]. These techniques are relatively fast (∼39 wpm [70]) but break immersion by forcing users to switch between the virtual and the actual worlds [166]. Furthermore, they require extensive tracking devices. Some attempted to address this by developing on-surface and mid-air virtual Qwerty [200, 55, 176, 143]. However, these approaches are not as effective as physical Qwerty (∼12 wpm [200]) due to the absence of haptic feedback [39, 55, 63]. Alternative input methods have also been explored, such as head pointing [239, 128, 200, 129] and eye pointing [172]. These methods are not only much slower than physical Qwerty (10–16 wpm [200, 172]) but also cause high physical strain in prolonged use [54]. A different approach overlays a new layout on the palm, enabling using the index finger of the other hand to type [218]. A similar approach splits Qwerty into two parts to assign each half to one of the hands and a group of keys to each finger, enabling users to enter text by pinching the thumb and fingers [59]. These methods are highly error-prone with error rates over 10%. Some have also used alternative input devices, such as handheld controllers [200, 151, 97], interactive gloves, rings, and straps [222, 228, 98, 233, 232], digital pens [96, 48], and smartphones [18, 81, 114, 73]. These techniques are also very slow (∼6–14 wpm [200, 114, 98]) and highly error-prone (15–35% [222, 96, 48]). For a comprehensive review of existing text entry techniques for virtual reality see our recent survey [54].

Key Design	**Reference**
Round 3D	[15, 16, 52, 166]
Square 2D	[15, 70, 73, 99, 172, 200, 227, 240]
Square 3D	[19, 53, 86, 157, 181, 200]
Hexagonal 3D	[40]

Table 2.1: Commonly used key shapes in Qwerty for virtual reality.

Although a range of novel techniques and technologies have been proposed, the most popular solution is still the virtual Qwerty. Despite these keyboards using the standard Qwerty layout, the design of the base and the keys vary (see Table 2.1). This lack of consistency has the potential to slow down the optimization of text input in virtual reality. Thus research is actively working on understanding the different aspects of text input in virtual reality. Grubert et al [69] investigated the impact of hand representation on typing in virtual reality. They found that using simple visualizations to represent the fingertips or providing a video feed can improve typing accuracy in VR without impacting speed. Rajana and Hansen [172] studied flat and curved keyboard bases in virtual reality. They found out that the entry speed with a flat base is significantly faster than with a curved

Figure 2.1: A Leap Motion Controller was attached to the front of the Oculus Rift at a 20° down angle to increase its field of view when the user's head is upright.

base. Outside virtual reality, the effects of keyboard shape [155], size [185], and background [234], and key size [38, 109] and spacing [38] on text entry performance have been explored. However, in virtual reality, we still do not understand the different aspects that impact text entry.

2.2 Experiment

This study investigated the effects of key shape and dimension on text entry performance and user experience.

2.2.1 Apparatus

We developed a custom system with Unity3D 2017.14.17 and Orion 4.4.0 SDKs. It ran on a Windows 10 HP OMEN desktop computer with an AMD Ryzen 5 2500X Quad-Core processor, 8 GB RAM, and an Nvidia GeForce GTX 1060 graphics card. It used an Oculus Rift[2] Head-Mounted Display (HMD). It also used a Leap Motion Controller[3] to track hands, which was attached to the front of the HMD at a 20° down angle to increase its field of view when the user's head is upright (Figure 2.1). We covered the base with a duvetyne[4] fabric (Figure 2.2) to absorb light since reflective surfaces affect Leap Motion's tracking ability [44]. We used Leap Motion regardless of its limitations [86, 156, 220] due to its availability and affordability.

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[2] Oculus Rift https://www.oculus.com

[3] Leap Motion Controller https://www.leapmotion.com

[4] Duvetyne https://en.wikipedia.org/wiki/duvetyne

Figure 2.2: The setup used in the study. The black material on the desk is duvetyne[4].

Figure 2.3: The abstract hand representation used in the study.

2.2.2 Design

The study used a within-subjects design with two independent variables: *key shape* and *key dimension*. Key shape had three levels: round, square, and hexagonal. Key dimension had two levels: 2D and 3D. In each condition, participants transcribed five random English phrases from a corpus [134]. The conditions were counterbalanced using a Latin square. The dependent variables were the performance metrics. In summary, the design was: 12 participants × 6 conditions × 5 phrases = 360 phrases in total.

2.2.3 Metrics

The study recorded the standard words per minute (wpm), error rate, and corrected error rate performance metrics. Words per minute is the average number of words entered in one minute, where a "word" is measured as five characters [4]. Error rate is the average percentage (%) of incorrect characters that remained in the final text. Corrected error rate is the average percentage (%) of incorrect characters corrected by the user (which are not in the final text).

Figure 2.4: A volunteer participating in the user study.

Key Design	**Area**
2D Round	19.63 cm^2
3D Round	70.69 cm^2
2D Square	25 cm^2
3D Square	150 cm^2
2D Hexagonal	16.24 cm^2
3D Hexagonal	62.48 cm^2

Table 2.2: Each key was designed to fit a 5×5 cm square, which acted as the active touch area for the keys. The height of the 3D keys were 2 cm.

Figure 2.5: The virtual environment used in the study. It had a wooden desk, the virtual keyboard on the desk, and a text input area floating above the desk.

2.2.4 Virtual Keyboard

We developed a custom virtual Qwerty that used round, square, and hexagonal keys in both 2D and 3D (Figure 2.6). These shapes were chosen since these are commonly used in Qwerty for virtual reality (Table 2.1). Table 2.2 displays the area covered by each key. All keys were positioned in a 5×5 cm active area with a 7 mm padding between the keys to facilitate comfortable 3D pointing [9]. Users saw a virtual representation of their hands (Figure 2.3). The keyboard provided visual feedback on each key press. The 2D keys were highlighted in a different color [227] and the 3D keys played a key-down animation mimicking actual keys [200]. The keyboard used a dark-blue background with light-grey keys and black font for better contrast. All keys used the same font and font size. Neutral colors were used as bright colors can cause visual fatigue [147]. Abstract hands were used to avoid the effect of gender and the "uncanny valley" [3, 184].

2.2.5 Virtual Environment

The virtual environment had a desk, the custom virtual Qwerty on the desk, and a text input area floating above the desk (Figure 2.5). When participants entered the virtual environment, they felt like they were sitting in a chair facing the desk. We used a minimalistic approach to design the environment to ensure that it did not distract the participants.

2.2.6 Participants

Twelve participants voluntarily took part in the study (Figure 2.4). Eight of them were female and four were male. Their age ranged from 19 to 32 years (M = 22.9, SD = 3.5). They all identified themselves as native or bilingual speaker of the English language. Three of them wore eyeglasses.

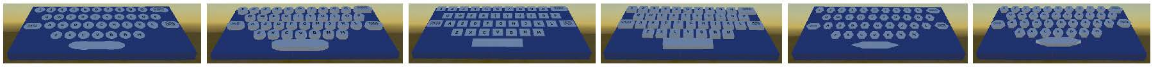

Figure 2.6: The six key designs used in the study, from left: 2D round, 3D round, 2D square, 3D square, 2D hexagonal, and 3D hexagonal.

They all were experienced Qwerty users. Four of them had used an HMD before, but none had experience typing in virtual reality.

2.2.7 Procedure

The study was conducted in a quiet room. Upon arrival, we explained the study procedure to all participants, collected their consents, and asked them to complete a demographics and experience questionnaire. They then participated in two 10-minute practice sessions. In the first session, they played around with their hands to get a feel of the virtual hands. In the second session, they typed the *"The quick brown fox jumps over the lazy dog"* pangram with either of the six key designs (Figure 2.6) in a counterbalanced order. These sessions were necessary since most participants were unfamiliar with virtual reality. Besides, these enabled us to observe any symptoms of virtual reality sickness[5] (none recorded in this study), adjust the headset, and calibrate the keyboard position for each user.

In the main study, participants transcribed five short phrases from a corpus [134] with each key design in a counterbalanced order. A random phrase was presented above the input area. Participants were instructed to read, understand, and memorize the phrase before transcribing it *as fast and accurate as possible*, then press the ENTER key to see the next phrase. Error correction was encouraged, but not enforced. There were 2-minute breaks between the conditions, where participants were instructed to remove the HMD. Upon completion of the study, participants ranked the key designs in terms of how natural they felt, speed, accuracy, and their overall preference.

2.3 Results

For statistical tests, we removed all instances where the user's hands were not visible due to tracking issues (7% of the data). We used repeated-measures ANOVA for all analysis as a Shapiro-Wilk test and a Mauchly's test confirmed that the filtered data did not violate its normality and sphericity assumptions, respectively.

2.3.1 Entry Speed

An ANOVA identified a significant effect of shape on entry speed ($F_{2,11} = 3.64$, p ¡ .05). The average entry speed with round, square, and hexagonal keys were 10.82 wpm (SD = 2.9), 11.83 wpm (SD = 2.9), and 10.92 wpm (SD = 2.7), respectively. A Duncan's test revealed that entry speed with square keys was significantly faster than with round keys. An ANOVA failed to identify a significant effect of dimension ($F_{1,11} = 2.16$, $p = .2$). The average entry speed with 2D and 3D keys were 10.75 wpm

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[5] Virtual Reality Sickness https://en.wikipedia.org/wiki/virtual_reality_sickness

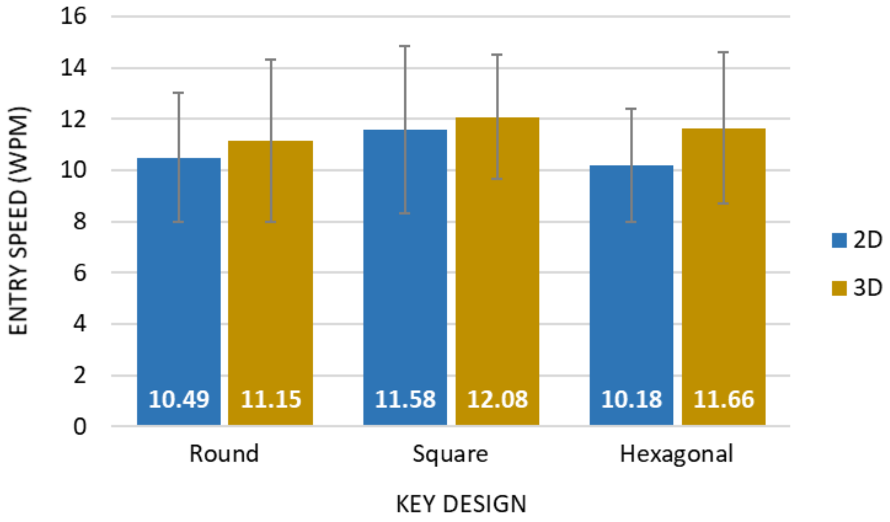


Figure 2.7: Average entry speed for the six different keys explored in the study. Error bars represent ±1 standard deviation.

(SD = 4.4) and 11.63 wpm (SD = 2.6), respectively. There was also no significant effect of shape × dimension ($F_{2,11}$ = 0.84, p = .4). Figure 2.7 illustrates average entry speed with all key designs.

2.3.2 Error Rate (%)

An ANOVA failed to identify a significant effect of shape on error rate ($F_{2,11}$ = 0.61, p = .5). The average error rate with round, square, and hexagonal keys were 4.79% (SD = 4.2), 4.35% (SD = 4.4), and 5.27% (SD = 3.2), respectively. However, there was a significant effect of dimension ($F_{1,11}$ = 10.03, p ¡ .01). The average error rate with 2D and 3D keys were 6.56% (SD = 4.4) and 3.04% (SD = 2.5), respectively. A Duncan's test revealed that error rate with 2D and 3D keys were significantly different. However, an ANOVA failed to identify a significant effect of shape × dimension ($F_{2,11}$ = 0.80, p = .5). Figure 2.8 illustrates average error rate for all key designs.

2.3.3 Corrected Error Rate (%)

An ANOVA failed to identify a significant effect of shape on corrected error rate ($F_{2,11}$ = 3.26, p = .05). The average corrected error rate with round, square, and hexagonal keys were 6.28% (SD = 5.8), 4.98% (SD = 4.6), and 4.57% (SD = 4.2), respectively. There was also no significant effect of dimension ($F_{1,11}$ = 4.54, p = .05). The average corrected error rate with 2D and 3D keys were 6.63% (SD = 5.9) and 3.92 (SD = 3.3), respectively. An ANOVA failed to identify a significant effect of shape × dimension as well ($F_{2,11}$ = 3.05, p = .06). Figure 2.9 illustrates average corrected error rate for all key designs.

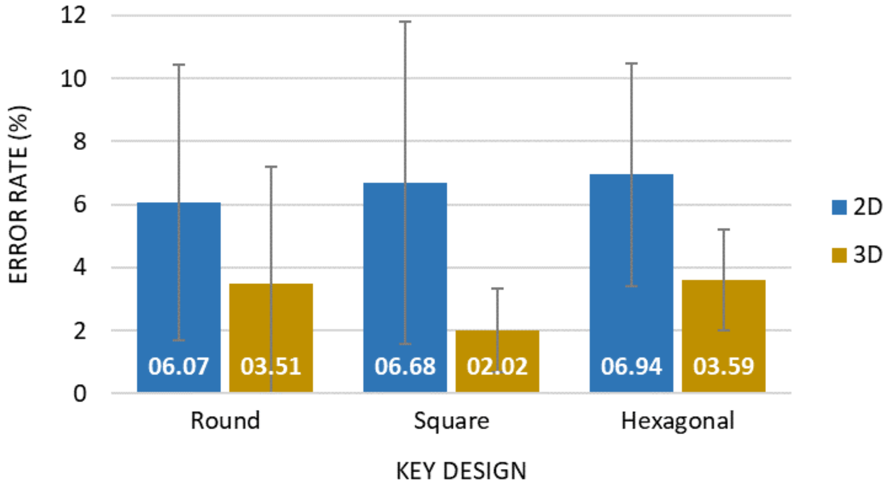


Figure 2.8: Average error rate for the six different keys explored in the study. Error bars represent ±1 standard deviation.

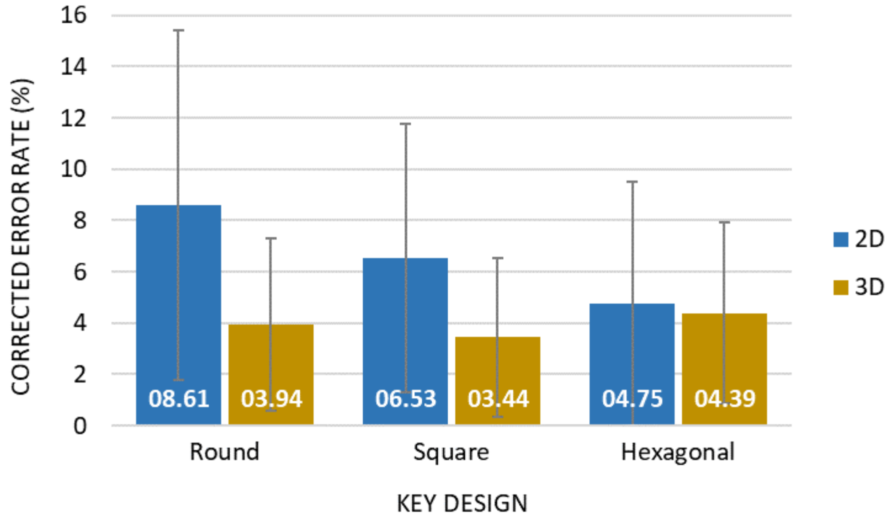


Figure 2.9: Average corrected error rate for the six different keys explored in the study. Error bars represent ±1 standard deviation.

Key Design	*Natural*	*Speed*	*Accuracy*	*Preference*
Round 2D	0	0	0	0
Round 3D	0	**2**	**2**	**1**
Square 2D	0	**2**	**2**	**2**
Square 3D	**12**	**8**	**8**	**8**
Hexagonal 2D	0	0	0	0
Hexagonal 3D	0	0	0	**1**

Table 2.3: User responses to the key designs they found the most natural, enhance entry speed and accuracy, and their overall design preference. The study involved 12 participants (N = 12).

2.3.4 Qualitative Data

Table 2.3 presents all user responses, where one can see that most participants found the square 3D keys the most natural. They also felt that square 3D keys enhanced their text entry speed and accuracy, thus wanted to use it in virtual reality. The square 2D keys were the second most preferred, followed by the round 3D keys. Participants were in agreement that the hexagonal keys were not natural and affected their entry speed and accuracy. Yet, one participant wanted to keep using the 3D hexagonal keys, because they *“looked cool”*.

Most participants preferred the 3D keys since they thought they imitated the behavior of an actual key the best. One participant commented that he liked the 3D keys because he is *“used to them from the real world”*. Participants who preferred 2D keys stated that they found the visual feedback on 3D keystrokes distracting (the key-down animation). One participant commented that she kept looking at the animation, which *”disturbed”* her typing.

2.4 Discussion

Results showed that entry speed with different key shapes were significantly different. Square keys yielded about 8% faster entry speed than round and hexagonal keys. Participant responses also corroborate this. Most participants (83%, N = 10) felt that their entry speed was much faster with square keys (Table 2.3) compared to the other keys. Text entry speed with 3D keys were also about 8% faster than 2D keys. This effect was not statistically significant. However, it appears that participants picked up on this behavior since most of them (83%, N = 10) responded that 3D keys enhanced their entry speed (Table 2.3). Although there was no significant effect of key shape on error rate, most participants (83%, N = 10) felt that square keys were more accurate than the other keys (Table 2.3). They were not totally amiss since round and hexagonal keys were 9% and 17% more error prone than square keys. There was a significant effect of key dimension on error rate. 3D keys were 54% more accurate than the other keys. Participants noticed this too, as most of them (83%, N = 10) responded that they were more accurate with 3D keys than 2D keys (Table 2.3). There was no significant effect of key size or shape on corrected error rate. This suggests that participants did not face any major difficulties in correcting errors with any of the keys.

Overall, 3D square keys yielded the best actual and perceived performance. These findings suggest that imitating the design and behavior of real-world objects in the virtual world is a good idea, especially at the infancy of the technology. Further qualitative research is needed to find out whether this finding can be generalized to a larger sample. We also stress the importance of revisiting this in the future since the need for imitating physical objects in the digital world often diminishes as technologies become ubiquitous.

2.5 Conclusion

We presented a study that investigated the effects of different key shapes and dimensions on text entry performance and user experience. Results revealed that key shape affects text entry speed, dimension affects accuracy, and both affect user experience. These findings will aid in designing keyboards that can facilitate faster, more accurate, and more pleasant text entry experiences in virtual reality.

Chapter 3

Mid-Air Ultrasonic Feedback

In the previous Chapter, we discussed a virtual Qwerty input setup where users typed on a desk surface. Although this method is practical in certain contexts, it comes with inherent limitations. The desk surface offered passive haptic feedback, which helped users confirm key presses by touch. However, this reliance on a physical surface constrains the versatility of the input method. It necessitates the presence of a physical object, which may not always be available or desirable, particularly in scenarios where space is limited or where users need to move freely. Furthermore, there are numerous situations in which users must rely entirely on mid-air gestures for interaction, emphasizing the need for more adaptable and flexible input methods in virtual environments.

Currently, the most popular text entry solutions in virtual reality are physical or mid-air virtual Qwerty, neither of which are ideal for entering text in VR [54]. Physical Qwerty breaks immersion by forcing users to switch between the virtual and the actual worlds [54], although this can be remedied by blending the appearance of the keyboard in the virtual world [141] and making the animation of the hand as realistic as possible [116]. Mid-air virtual Qwerty improves presence in virtual reality since it eliminates the need for a physical keyboard, but it lacks tactile feedback. With physical Qwerty, users feel an opposite force when pressing down a key and can use the keys as a spatial reference. The absence of this feedback affects text entry performance with mid-air virtual keyboards.

While there have been attempts to introduce various haptic feedback methods for mid-air interaction in virtual reality, most approaches rely on either impractical external hardware or wearable devices like rings or gloves. To enhance the mid-air virtual Qwerty experience, we need a method that provides seamless haptic feedback without any external devices. This would allow users to experience the tactile sensation of typing while maintaining the freedom and convenience of unencumbered hands. In this Chapter, we augment a mid-air virtual Qwerty with ultrasonic haptic feedback that does not require any hardware on the user's hands. Building on the results of the previous study, which informed the design of the virtual Qwerty, we take the following approach: First, we compare three different types of ultrasonic feedback in a pilot study. We identify the best-performed feedback, then use it with a mid-air Qwerty. We compare the keyboard with haptic feedback (ultrasonic keyboard) with another keyboard without haptic feedback in a user study.

The remainder of this Chapter is structured as follows. We begin with a review of related work, followed by descriptions of our pilot study and main user study (including feedback development, apparatus, experimental design, and participant details). Next, we present and discuss our findings. Finally, we conclude by summarizing the key findings of the work. All studies reported here were approved by the Institutional Review Board (IRB) and were conducted in accordance with the institute's preventive measures for COVID-19.

3.1 Related Work

3.1.1 Text Entry in Virtual Reality

In Section 2.1, we summarize the current methods for text input in virtual reality. Freehand text input remains a popular choice as it aligns well with the immersive nature of VR and eliminates the need for complex hand tracking or instrumentation. Additionally, unlike novel input devices, it requires minimal learning for users. However, the lack of haptic feedback significantly affects text entry performance. Numerous works explored mid-air text input in VR without haptic feedback [200, 99, 219], the studies reported text entry speed of between 10-12 wpm. There is a need to provide haptic feedback to improve user experience and performance.

In the previous study, we used passive haptics (a desk surface) to provide tactile feedback. This approach has been successfully employed to achieve typing speeds of up to 55 words per minute for touch typists in VR [55]. However, to achieve such speeds it relies on a decoder and experienced users (touch typist). Reliance on the decoder makes it difficult to input out of vocabulary words. Table 3.1 summarizes the methods used to provide haptic feedback for text entry in VR. Desk surfaces offer low-fidelity haptic feedback, which does not always align with what the user sees in the virtual environment. For instance, a virtual key might appear unsupported in mid-air, yet provide a solid sensation due to the underlying desk. This mismatch can create a disjointed experience.

3.1.2 Haptic Feedback in Virtual Reality

The lack of tactile feedback in mid-air interaction has prompted research into unorthodox haptic feedback approaches. Gupta et al. used wearable actuators to provide remote vibrotactile feedback on the wrist and the base of the finger [74]. In an evaluation, both feedback methods performed comparably, however, participants preferred the feedback on the finger since it felt more natural. Some used digital gloves to provide vibrotactile feedback on the hand and the fingertips [228, 204, 72]. Muthukumarana et al. used shape memory alloys to provide touch sensation on the forearm [149]. Lopes et al. used a full-body suit and objects attached to the elbows and the shoulders to induce electrical muscle simulation [127]. Gupta et al. provided mid-air haptic feedback through air vortex [76]. Some have also explored haptic feedback through ultrasound [29, 66, 173]. These methods, however, have not been explored or evaluated in the context of text entry.

3.1.3 Ultrasonic Haptic Feedback

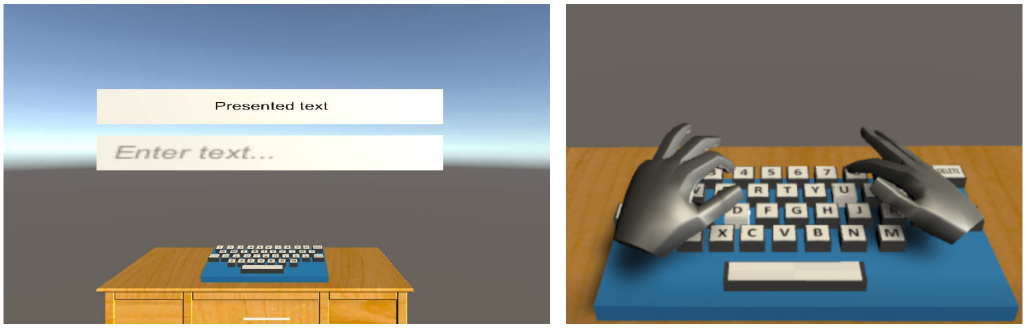
Ultrasonic haptic feedback, proposed in early 2000s [87, 88], is a non-intrusive solution that provides touch sensation by sending ultrasonic waves to a target (e.g., fingertip) at different wavelengths [29, 213]. The shear wave induced in the skin tissue triggers the mechanoreceptors within the skin to generate a haptic sensation that is somewhat comparable to a vibratory sensation. The mechanoreceptors respond to vibrations between 0.4 to 500 Hz. For a comprehensive review of ultrasonic haptic feedback and its applications see a recent survey [174].

Table 3.1: Performance of free-hand text entry techniques with haptic feedback reported in the literature. “Method”, “target”, and “haptic” represent the medium used to provide haptic feedback, the body-part targeted for feedback, and the type of feedback provided, respectively. “Surface” signifies hard flat surfaces, such as a desk. The symbol “γ” signifies two fingers, “σ” ten fingers, “α” one part of the wrists, and “τ” different parts of the wrists.

Method	Target	Haptic	WPM	ER (%)
Surface (Chapter 2)	Fingertip	Passive	12.08	2.02
Surface [143]	Fingertip	Passive	-	-
Surface [55]	Fingertip$^{\gamma}$	Passive	55.5	4
Surface [55]	Fingertip$^{\sigma}$	Passive	51.6	7
Wearable [228]	Fingertip	Vibrotactile	-	-
Wearable [74]	Wrist$^{\alpha}$	Vibrotactile	22.5	13.5
Wearable [74]	Wrist$^{\tau}$	Vibrotactile	22.8	14.8
Wearable [74]	Fingerbase	Vibrotactile	23.0	11.2

3.2 The Ultrasonic Keyboard

We developed the experimental system using Unity3D 2019.4.8f1, Leap Motion Orion 4.0.0 SDK, Leap Motion Unity Core Assets 4.4.0, and Ultraleap Unity Core Assets 1.0.0 Beta 9. The virtual environment consists of a desk, a keyboard, and a text input area above the desk (Fig. 3.1a). We kept the environment simple to avoid any distractions and used neutral colors to reduce visual fatigue [147] during text entry. Besides, we designed the environment to be immersive so that the user feels that they are sitting in front of a desk.



(a) The virtual environment

(b) The keyboard and the abstract hands

Figure 3.1: (a) The virtual environment developed for this research and (b) the mid-air Qwerty keyboard with abstract virtual representations of the hands.

3.2.1 Keyboard Design

We developed a 1335.5 × 478.5 px (307 × 110 mm) virtual Qwerty (Fig. 3.1b), which has a dark-blue base and 91.4 × 91.4 × 30.5 px (21 × 21 × 7 mm) keys with light-grey top and black sides and labels. This color combination was picked to aid contrast. The size of the keyboard was influenced by the effective interaction area of the ultrasonic haptic board (Section 3.2.2). We used square-shaped 3D keys since we found that square-shaped keys improve text entry speed, while 3D keys improve accuracy (see Chapter 2). The keyboard provides visual feedback on both hover and press. When the finger is 108.8 px (25 mm) above a key, the sides of the key change color from black to light-grey. Likewise, when the user presses down the key, it plays a key-down animation to mimic an actual key. The keyboard does not provide any auditory feedback. A Leap Motion Controller [208], attached upward to the haptic board, tracks both hands at 200 fps, and then presents their virtual representations to the user. It uses a dark-grey abstract hand representation (Fig. 3.1b) for gender neutrality and to avoid the effect of the uncanny valley [69, 3]. Although the keyboard can track all fingers, we focused only on two-finger typing using the index fingers since prior work found two-finger typing to be substantially faster than ten-finger typing with mid-air virtual Qwerty in VR [55].

3.2.2 Haptic Sensation

The system uses an Ultraleap STRATOS Explore [209] haptics board (242 × 207 × 34 mm, 0.7 kg) to provide mid-air haptic feedback (Fig. 3.2a). The device is a phased array composed of 16 × 16 transducers that operate at a frequency of 40 kHz. The ultrasound waves produced by the transducers can be focused on a point in a 400 × 400 mm plane about 600 mm above the device. When focused on the hand or a finger, the mechanoreceptors in human skin sense the waves as pressure or vibration [29]. The experimental system tracks the hand and the fingers using the Leap Motion Controller (for technical details refer to Section 3.2.1), then aims ultrasound waves at the tip of the index finger. The device limits interactions between 200 to 600 mm above the haptics

(a) Ultraleap STRATOS Explore (b) The complete experimental setup

Figure 3.2: (a) The haptics device with the transducers exposed. In the study, they were covered with a metal cover that came with the device, (b) The Ultraleap device was placed on a small table (height: 52 cm) closer to the users for comfortable mid-air actions.

device. We designed three different types of ultrasonic haptic feedback using the Ultraleap Unity Core Assets 1.0.0 Beta 9, described below. These feedback methods simulated touch sensations using spatiotemporal modulation [91, 65] with a drawing frequency of 70 Hz.

- **Touch & press feedback** provides haptic feedback on both touch and keypress. When the finger touches a key, the keyboard provides haptic feedback of the shape of the key at 60% intensity. When the finger presses down the key beyond the 30.5 px (7 mm) threshold, it provides the same feedback at 100% intensity. We designed the feedback to match the shape of the key to resemble the haptic feedback of an actual keyboard. Besides, we compared the square-shaped feedback with a Lissajous curve feedback in a pilot study (N = 3, M = 29.3 years), where the former was the most preferred by the participants because it felt more natural and covered a larger area. The feedback remained active until users moved their finger away from the key.
- **Press feedback** provides haptic feedback only on keypress. It uses the same convention used for press by the touch & press feedback.
- **Gradual feedback** also provides feedback on both touch and press. However, instead of providing two distinct levels of feedback, it gradually increases the intensity of the feedback relative to the distance the key is depressed. More specifically, when the finger touches a key, the keyboard provides haptic feedback at 60% intensity, then gradually increases to 100% as the user presses down the key.

Fig. 3.3 illustrates the operation area in the experiments.

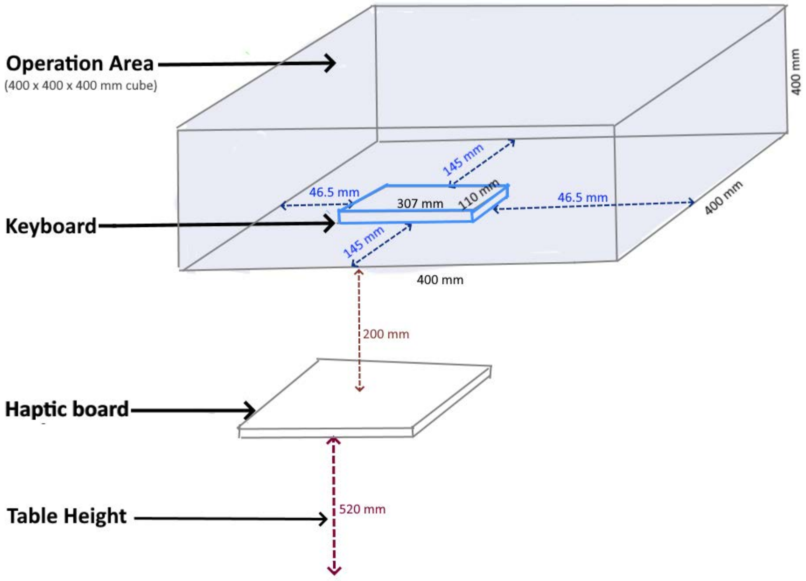


Figure 3.3: The operation area in the experiment setup (the shaded area).

3.3 Pilot Study: Three Feedback Methods

We conducted a pilot study to compare the three feedback methods in text entry tasks.

3.3.1 Participants

Six volunteers participated in the pilot study. Their age ranged from 21 to 37 years (M = 27.5, SD = 5.1). Three of them identified themselves as women and three as men. They all were native or bilingual English speakers. None of them wore corrective eyeglasses. Two of them had used a virtual reality system in the past, but none of them owned an HMD. None of them had prior experience with ultrasonic feedback. They all received U.S. $10 for participating in the study.

3.3.2 Apparatus

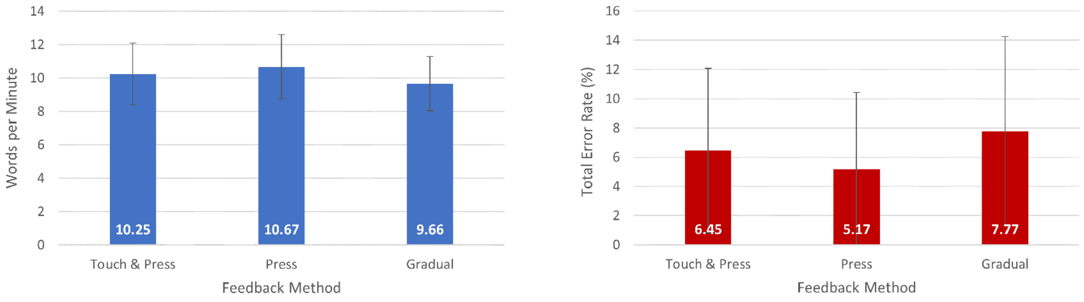
We used an ASUS ROG GU501GM Gaming Laptop with an Intel core i7 processor, 16 GB ram, NVDIA GeForce GTX 1060 graphics card, running on a Windows 10 OS. We used an Oculus Rift HMD with 110° field of view and 90 Hz refresh rate. Participants were seated on a chair resting their arms on the armrest to reduce the gorilla arm effect [82]. The Ultraleap Stratos Explore haptic board was placed on top of a small table (height: 52 cm) in front of the user. Fig. 3.2b illustrates the complete setup.

3.3.3 Design & Procedure

The study used a within-subjects design with one independent variable (feedback) with three levels (touch & press, press, and gradual). In each condition, participants transcribed 12 random English phrases from a set [134]. The conditions were counterbalanced in a Latin square to eliminate the effect of learning. The dependent variables were the commonly used words per minute (wpm) and total error rate (TER) performance metrics in text entry research [4]. TER, unlike the conventional error rate, accounts for both corrected and uncorrected errors in the calculation of error rate [197]. The study was conducted in a quiet room. First, we described the research to all participants, and collected their informed consent and demographics. We then demonstrated the system and the three feedback methods, and enabled them to practice with the system by entering 5 phrases with each feedback method. These phrases were not repeated in the study. Then, we started the main study, where the system displayed one random phrase at a time above the input area. Participants were instructed to transcribe the phrase as fast and as accurately as possible. Error correction was recommended but not forced. Once done with a phrase, they pressed the “Enter” key to see the next phrase. This process continued until they were done with all phrases in a condition. We enforced a 5-minute break between the conditions to reduce the effect of fatigue. However, participants could extend the break when needed. The system automatically calculated and recorded the performance metrics. Upon completion of all conditions, participants were asked to pick their most preferred feedback method and justify the choice.

3.3.4 Results & Discussion

A repeated-measures ANOVA identified a significant effect of method on entry speed ($F_{2,5} = 7.28, p < .05$). On average entry speed with the touch & press, press, and gradual feedback were 10.25 wpm



(a) Entry speed (wpm) (b) Total error rate (%)

Figure 3.4: Average text entry speed (wpm) and total error rate (%) with the three examined feedback methods. Error bars represent ±1 standard deviation (SD).

(SD = 1.85), 10.67 (SD = 1.93), and 9.66 wpm (SD = 1.62), respectively (Fig. 3.4a). A post-hoc Tukey-Kramer test identified entry speed with gradual feedback to be significantly slower compared to the other methods (∼6–9% slower). An ANOVA failed to identify a significant effect of feedback method on total error rate ($F_{2,5} = 2.52, p = .13$). Average TER with the touch & press, press, and gradual feedback were 6.45% (SD = 5.62), 5.17% (SD = 5.26), and 7.77% (SD = 6.48), respectively (Fig. 3.4b). In the post-study discussion, four participants preferred the touch & press feedback as they found it to be the most natural and effective. With this feedback they could sense the keys before pressing them, thus could use it as spatial reference, which they believed improved their performance with the method. Two participants preferred the press feedback, because they felt with touch & press, sometimes it was difficult to tell whether they had pressed the key or not. A participant (female, 28 years) commented, *"It [press] is better [..] because I know I pressed something for sure."* In summary, hover & press yielded the best performance both qualitatively and quantitatively. Hence, we used it in the final study.

3.4 User Study: Haptic v. No-Haptic

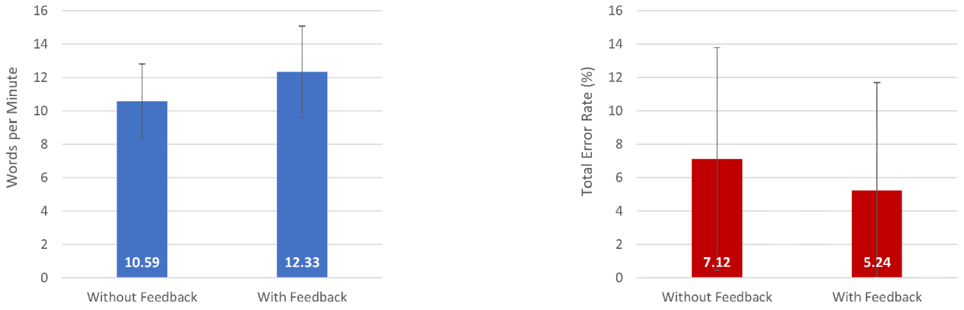
We conducted a user study to compare a virtual keyboard *with* touch & press feedback and *without* feedback to investigate the effects of haptic feedback on mid-air text entry performance in VR.

3.4.1 Participants & Apparatus

Twelve participants took part in the study. None of them participated in the pilot studies. Their age ranged from 21 to 37 years (M = 27.9, SD = 6.0). Four of them identified themselves as women and eight as men. They all were native or bilingual English speakers. Two of them wore corrective eyeglasses. Five of them had used a virtual reality system in the past, but none of them owned an HMD. None of them had prior experience with ultrasonic feedback. They all received U.S. $10 for participating in the study. The study used the same apparatus as the pilot study (Section 3.3.2).

3.4.2 Design & Procedure

The study used a within-subjects design with one independent variable (feedback) with two levels (with, without feedback). In each condition, participants transcribed 12 random English phrases from a set [134]. The conditions were counterbalanced in a Latin square to eliminate the effect of learning. The study used the same dependent variables and procedure as the pilot study (Section 3.3.3). However, in this study, we asked participants to complete a custom usability and the NASA-TLX [79] questionnaires upon completion. They then took part in a brief informal interview session.



(a) Entry speed (wpm)

(b) Total error rate (%)

Figure 3.5: Average text entry speed (wpm) and total error rate (%) with and without haptic feedback. Error bars represent ±1 standard deviation (SD).

3.4.3 Results

3.4.3.1 Entry Speed

A paired samples T-test identified a significant effect of haptic feedback ($t_{143} = 6.94, p < .0001$) on text entry speed. The average speed with and without haptic feedback were 12.33 wpm (SD = 2.75) and 10.59 wpm (SD = 2.23), respectively (Fig. 3.5a).

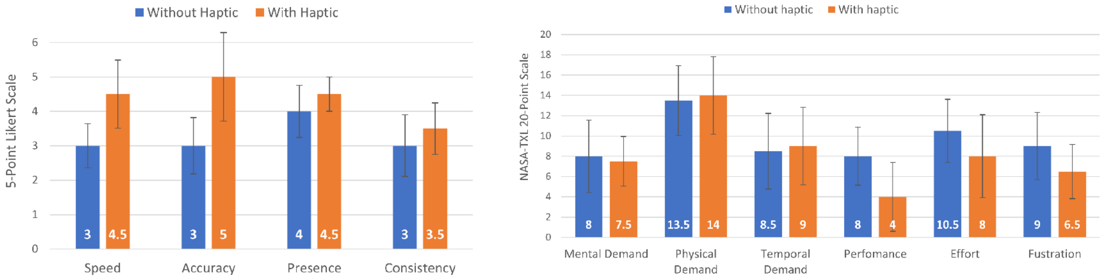
3.4.3.2 Error Rate

A paired samples T-test identified a significant effect of haptic feedback ($t_{143} = 2.52, p < .05$) on total error rate. The average error rate with and without haptic feedback were 5.24% TER (SD = 6.12) and 7.12% TER (SD = 6.65), respectively (Fig. 3.5b).

3.4.3.3 Usability

In the usability questionnaire, we asked participants to rate the perceived speed, accuracy, presence (felt physically present and accepted the reality of it), and consistency with real-world (the system seemed consistent with real-world experience) on a 5-point Likert-scale (1: disagree – 5: agree). A Wilcoxon Signed-Rank test identified a significant effect of feedback on perceived speed ($z = 2.322, p < .05$), presence ($z = 2.236, p < .05$) and consistency with real-world ($z = 2.332, p < .05$).

However, no significant effect was identified on perceived accuracy ($z = 1.715, p = .08$). Fig. 3.6a illustrates median user ratings of the two methods.



(a) Median usability ratings

(b) Median raw NASA-TLX ratings

Figure 3.6: Median usability and raw NASA-TLX ratings of the keyboard with and without haptic feedback. Error bars represent ±1 standard deviation (SD).

3.4.3.4 Perceived Workload

In the NASA-TLX questionnaire, participants rated the perceived workload of the examined method on a 20-point scale (1: very low – 20: very high, except for "performance", where 1: perfect – 20: failure). Here, we present raw scores by analyzing the sub-scales individually, which is a common modification of the scale [78]. A Wilcoxon Signed-Rank test identified significant effects of haptic method on mental demand ($z = -1.999, p < .05$), performance ($z = -2.07, p < .05$), effort ($z = -2.598, p < .01$) and frustration ($z = -2.057, p < .05$). However, no significant effects were identified on physical demand ($z = -1.378, p = .16$) and temporal demand ($z = 1.06, p = .92$). Fig. 3.6b illustrates median NASA-TLX ratings of the two methods.

3.4.4 Discussion

The keyboard with haptic feedback outperformed the keyboard without haptic feedback both in terms of speed (16% faster) and accuracy (26% more accurate). Participants perceived the keyboard with haptic feedback to be significantly faster (Fig. 3.6) and felt that it improved their overall text entry performance (Fig. 3.6b). These results are most probably facilitated by the increased spatial awareness of the participants, reducing their reliability on sight and proprioception to press the keys. In the post-study interview, one participant (male, 22 years) commented, *"I can type and know I pressed the key, I do not need to look that much."* Most participants were also more confident with haptic feedback. One participant (female, 36 years) felt that she performed much better with haptic feedback because *"I was more confident with my button presses when there is haptic feedback."* Naturally, participants found the keyboard with haptic feedback significantly less demanding in terms of mental demand and effort, thus caused significantly less frustration during text entry (Fig. 3.6b). Subjective feedback revealed that participants felt physically present and perceived their text entry experience comparable to real-world experience significantly more when interacting with the virtual keyboard with haptic feedback (Fig. 3.6a). In post-study interview, participants attributed these to the fact that they could sense the keys and receive feedback on keypress like actual keyboards.

They articulated that they could use haptic feedback on touch as a “physical” point of reference, which helped them better orient in mid-air interaction by increasing spatial awareness. Yet, participants found both methods comparable in terms of physical and temporal demands (Fig. 3.6b). We speculate this is due to the physical challenges associated with mid-air interaction in general.

Overall, the haptic sensation was well-received by the participants. Many compared the sensation with wind or vibration. One participant (female, 27 years) commented, *“I felt like wind is hitting my finger”*, while another (male, 23 years) said, *”I could feel the vibration on my finger.”* They found the sensation *“cool”* and *“pretty good”*. However, two participants were not comfortable with it. One of them (female, 26 years) said that it *“annoyed”* her, the other (male, 22 years) compared the sensation with *“static electricity”*, thus *“too artificial for my liking.”* Although text entry performance of these two participants were either better with haptic feedback or comparable to without haptic feedback. This suggests further investigation is needed to make ultrasonic sensations more comparable to actual touch.

3.5 Conclusion

We designed three different types of ultrasonic haptic feedback to provide a better text entry experience with a mid-air Qwerty in virtual reality: feedback on keypress, feedback on both touch and keypress, and a gradual feedback that increases intensity as users push down a key. We compared the three feedback methods in a user study. Results revealed that text entry speed was significantly faster with both touch & press feedback and press feedback than gradual feedback, but participants found touch & press more natural than the others. We then compared a mid-air Qwerty with and without touch & press feedback in a user study. Results revealed that haptic feedback improved speed by 16% and reduced error rate by 26%. Most importantly, majority of the participants felt that the feedback improved their presence and spatial awareness in the virtual world by maintaining a higher consistency with the real world. They also felt that the feedback reduced mental demand, effort, and frustration in text entry tasks, and thus wanted to continue using it.

Chapter 4

Mid-Air Selection with Ultrasonic Feedback

While the findings from the previous Chapter highlighted the advantages of ultrasonic feedback for horizontal interactions, it raised an important question: *Can these benefits extend to the distinct challenges associated with vertical mid-air gestures?* To explore this, we investigate the application of ultrasonic feedback in combination with common mid-air selection gestures. This approach aims to determine whether the tactile enhancements provided by ultrasonic technology can effectively support more complex and diverse gesture orientations, potentially expanding the usability and intuitiveness of gesture-based interactions in virtual environments. In VR, mid-air gestures are also commonly used in a vertical setup. Furthermore, due to the growing availability, affordability, and reliability of commercial gesture recognition products (e.g., Leap Motion Controller and Microsoft Kinect) there is also an increased use of three-dimensional (3D) mid-air gestures to interact with two-dimensional (2D) displays (e.g., interactive tabletops and walls, smart televisions, and desktop monitors) and content (e.g., menus and keyboards).

However, due to the unreliability of early tracking systems and gesture recognition methods, early work in the area focused on improving gesture detection and recognition. There is also considerable work on eliciting mid-air gestures from users to increase their guessability [214]. The spread of COVID-19 has also inspired interest in investigating mid-air gestures to enable contactless interaction with public devices, including ATMs and kiosks [66, 93]. However, there is little focus on comparing the common mid-air selection gestures among themselves.

Furthermore, as we discussed previously, mid-air gestures often lack the spatial feedback crucial for accurate interaction. This feedback enables us to understand spatial relationships and perform actions relative to physical objects. We experience real-world 3D reality by exploring spatial relationships between real-world objects and perform gestures relative to these objects. To address this challenge, we will explore the use of ultrasonic haptic feedback to provide spatial cues in virtual environments for vertical interactions. While various haptic feedback mechanisms exist (including vibrotactile wearables, ultrasound, magnetic repulsion, and air vortex), most studies focus on comparing these novel methods with traditional visual and auditory feedback. We seek to go further by directly comparing the effects of different types of haptic feedback (such as proximity-based and action-based) on the performance of mid-air gestures.

In this Chapter, we compare the four most commonly used mid-air selection methods (*Push*, *Tap*, *Dwell*, *Pinch*) [27] with two types of ultrasonic haptic feedback (*Select*, *Hover & Select*). We used a Fitts' law experiment to identify the best-performed and most preferred mid-air gestures and haptic feedback methods for target selection.

The remainder of this Chapter is structured as follows. First, we review related work. Next, we describe the Fitts' law protocol, followed by a detailed explanation of our experimental system (including setup, participants, and design). We then present our results, offering a thorough discussion of the findings. Finally, the Chapter concludes with design recommendations based on the results.

4.1 Related Work

4.2 Mid-air Interaction

The advances of hand tracking technologies have seen the use of mid-air interaction rising [24]. Performing mid-air gestures is considered a more natural and intuitive mode of interaction than traditional interaction methods as it enables direct control of virtual objects using analogies from the real-world [83, 223, 27, 117, 67]. Yet, the most commonly used mid-air gestures are not well investigated for desktop, situated displays, and VR. There is a large body of work on eliciting and gathering intuitive mid-air gestures for desktop, situated, and large displays [224, 216, 226] and virtual and augmented reality [7]. Researchers have also investigated mid-air hand and whole-body gestures on various platforms, including desktop and situated displays [8, 101, 186, 61, 31, 100, 104], large public displays and spaces [217, 164, 146, 1], and augmented and virtual reality [27, 158, 217, 11, 60]. Some have also combined mid-air gestures with other interaction modalities, particularly touch [146], physical buttons [23], eye-gaze [148, 31, 165], and speech [80] to enable multi-modal interaction. Most of this work, however, focuses on comparing mid-air gestures with traditional interaction methods rather than comparing the most commonly used mid-air gestures with each other in terms of performance, user preference, and comfort [117].

Push, *Tap*, *Dwell*, and *Pinch* are the most commonly used mid-air gestures for target selection [8, 100, 101, 210]. [8] compared *Tap* with a mouse in a one-dimensional (1D) Fitts' law experiment, where the gesture yielded a 36% lower throughput (2.7 bps) than the mouse (4.2 bps). [61] conducted a 1D Fitts' experiment to compare the *Pinch* gesture with and without vibratory haptic feedback provided via a digital glove. The study failed to identify any significant difference between the two methods (both yielded about 2.5–3 bps throughputs). [101] compared *Dwell* (500 ms) with a mouse and a touchpad in a two-dimensional (2D) Fitts' law experiment. In the study, the gesture yielded 45% and 28% lower throughputs (2.6 bps) than the mouse (4.8 bps) and the touchpad (3.7 bps), respectively, with the dominant hand. In a similar study, [100] compared *Forward–Backward Push* with a mouse in a 2D Fitts' law experiment, where the gesture yielded a 71% lower throughput (1.2 bps) than the mouse (4.0 bps). The gesture investigated by Jones, McIntyre, and Harris is different than the one studied in this work. Jones, McIntyre, and Harris required users to make a forward then a backward push, while in our work users only had to make a forward push to select a target. [186], in contrast, compared *Tap* with a mouse and a bimanual "grab" gesture. In the study, *Tap* yielded 54% and 15% lower throughputs ($\sim$2.3 bps) compared to the mouse ($\sim$5.0 bps) and the bimanual gesture ($\sim$2.7 bps), respectively. In a different line of research, [27] showed that users find pointing with the index finger the most natural compared to other pointing approaches. Table 4.1 summarizes the findings of these works.

Table 4.1: Performance of mid-air selection methods from the literature. Only the highest reported means are listed. “Pro.” signifies Fitts’ law experimental protocol, “Leap” indicates Leap Motion Controller, “IR” signifies infrared cameras, “Bps” indicates throughput in bits/second, and ”Bi.” signifies bimanual.

Reference	**Gesture**	**Pro.**	**Baseline**	**Tracker**	**Haptics**	**Bps**
[8]	*Tap*	1D	*Mouse*	Leap	None	2.7
[61]	*Pinch + Vibration*	1D	*Pinch*	IR	Vibratory	3.0
[100]	*For-Back Push*	2D	*Mouse*	Leap	None	1.2
[101]	*Dwell (500 ms)*	2D	*Mouse, Touchpad*	Leap	None	2.6
[186]	*Tap*	2D	*Mouse, Bi. Gesture*	Leap	None	2.3

4.3 Haptic Feedback

In the real world, we experience 3D reality by experimenting with spatial relationships between tangible objects, and tend to perform gestures relative to these objects [83, 191]. Mid-air gestures are difficult to perform in 3D user interfaces due to the lack of this spatial reference. This increases the physical and cognitive efforts needed to perform these gestures and compromises their performance by affecting both speed and accuracy. Many novel mid-air haptic feedback methods have been proposed to address these, including vibrotactile feedback [119, 241, 120, 205, 140, 182], magnetic field repulsion [221], and air vortex [193, 196, 76]. Augmenting mid-air gestures with a mid-air haptic feedback method has shown to improve user performance and the overall interaction experience [66, 121, 91, 212, 179]. [10] reported that providing users with spatial reference in 3D selection tasks reduces the effort needed to perform the tasks. [39] demonstrated that mid-air interaction accompanied by mid-air haptic feedback increases users’ intentional binding. Yet, most of these methods require users to wear digital bands, rings, or gloves, or use extramural devices that are bulky, intrusive, and often impractical.

4.3.1 Ultrasonic Feedback

Ultrasonic haptic feedback is a non-intrusive solution that provides touch sensation by sending ultrasonic waves to a target (for more details refer to Section 3.1.3). While this method has been compared in empirical studies with traditional feedback methods like auditory and visual [121, 29, 213], to the best of our knowledge, no prior work has investigated the effects of different types of ultrasonic haptic feedback on the performance of the most commonly used mid-air gestures for target selection.

4.4 Fitts’ Law Protocol

Fitts’ law is a well-established method for evaluating target selection on computing systems [133]. In the 1990s, it was included in the ISO 9241-9 (revised: ISO 9241-411) standard for evaluating non-keyboard input devices by using Fitts’ throughput as a dependent variable [198]. The most common multi-directional protocol evaluates target selection movements in different directions. The task is

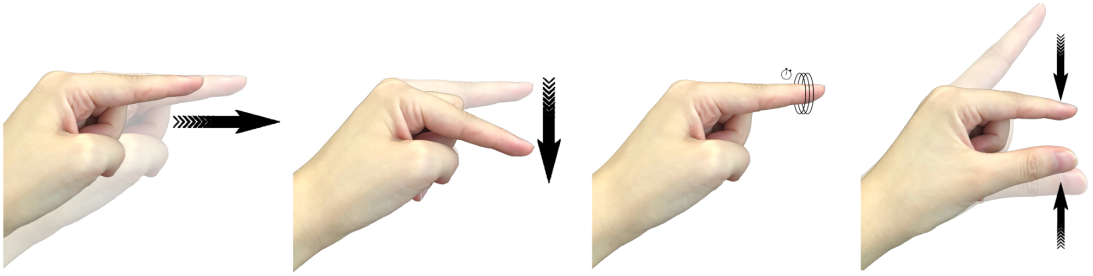
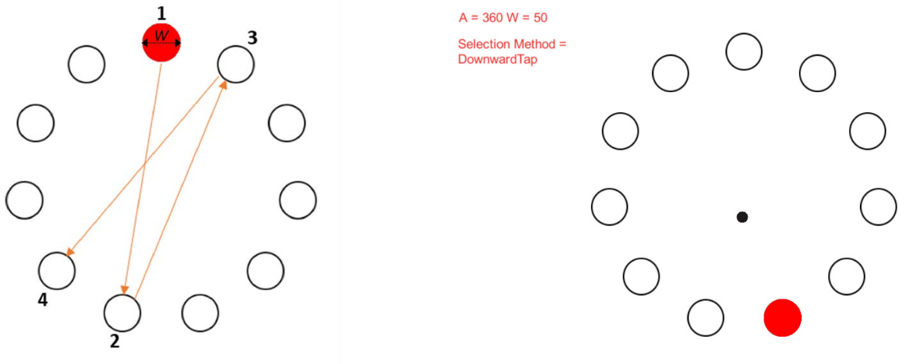


Figure 4.1: The four mid-air selection methods explored in this work, with two types of ultrasonic haptic feedback. From left, *Push*, users move the index finger forward like pushing an elevator key, *Tap*, users flick the index finger downwards like tapping on a touchscreen, *Dwell*, users hold the current position of the index finger for 800 ms, and *Pinch*, users pinch using the thumb and index finger.



A = 360 W = 50

Selection Method = DownwardTap

(a) The 2D Fitts' law task in ISO 9241-9

(b) A screenshot of the custom Unity application

Figure 4.2: (a) The target to select is highlighted in red. The arrows and numbers demonstrate the selection sequence. (b) Example sequence of trials. The black dot is the cursor.

2D with targets of width W equally spaced around the circumference of a circle (Fig. 4.2a). Participants select the targets in a sequence moving across and around the circle, starting and finishing at the top target. Each movement covers an amplitude A, which is the diameter of the layout circle. A *trial* is defined as one target selection task, whereas completing all tasks with a given amplitude is defined as a *sequence*. Throughput cannot be calculated on a single trial because a sequence of trials is the smallest unit of action in ISO 9241-9. Traditionally, the difficulty of each trial is measured in bits using an index of difficulty (ID), calculated as follows:

$$ID = log_2(\frac{A}{W} + 1) \tag{4.1}$$

The movement time (MT) is measured in seconds for each trial, then averaged over the sequence of trials. It is then used to calculate the performance throughput (TP) in bits/second (bps) using the following equation:

$$TP = \frac{ID}{MT} \tag{4.2}$$

The revised ISO 9241-9 (9241-411) used in this work [92] measures throughput using an effective index of difficult ID_e, which is calculated from the effective amplitude A_e and the effective width W_e to make sure that the real distance traveled from one target to the next is measured. It also takes into account the spread of selections about the target center.

$$TP = \frac{ID_e}{MT} \tag{4.3}$$

$$ID_e = log_2(\frac{A_e}{W_e} + 1) \tag{4.4}$$

The effective amplitude is the real distance traveled by the participants, while the effective width is calculated as follows, where SD_x is the standard deviation of the selection coordinates projected on the x-axis for all trials in a sequence. This accounts for any targeting errors by the participants, assuming that participants were aiming at the center of the targets.

$$W_e = 4.133 \times SD_x \tag{4.5}$$

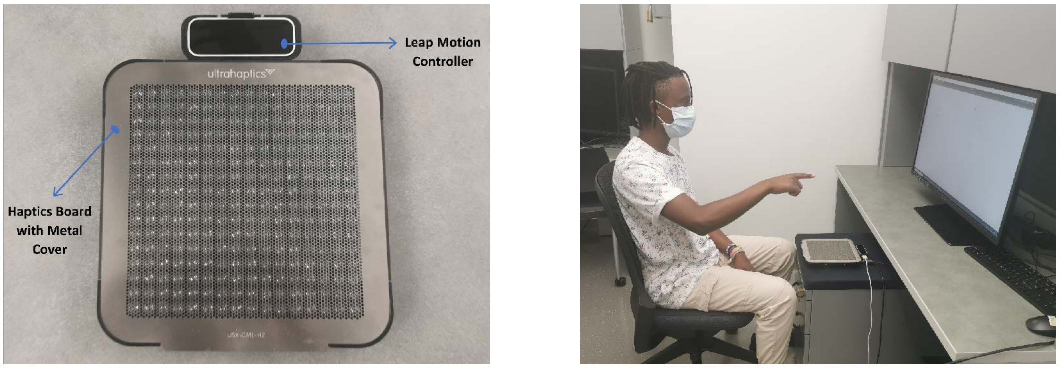
4.5 Experimental System

We developed the experimental system with Unity3D 2019.4.8f1, Leap Motion Orion 4.0.0 SDK, Leap Motion Unity Core Assets 4.4.0, and Ultraleap Unity Core Assets 1.0.0 Beta 9. The system enables users to control a cursor on a computer display by moving the hand. A Leap Motion Controller [207] tracks hand movements 200 mm above the surface, which is the ideal distance recommended by the manufacturer [208], and translates its position into x-y coordinates of the cursor on a vertical display. The system uses the following four most commonly used mid-air gestures for target selection (Fig. 4.1) [8, 100, 101, 210].

- **Push.** With this method, users point at a target with the index finger then make a forward push to select it. Due to human physiology, this also moves the hand forward, which we exploited to detect *Push* gestures. Based on multiple trials, we used a threshold of 100 mm/s—when the forward velocity (i.e., along the z-axis) of the palm is over this threshold, a push is detected, otherwise, the system interprets it as movements to position the cursor.
- **Tap.** With this method, users point at a target with the index finger then flick the finger downwards to select it. The system detects a tap based on the angle of the index finger. When users point at a target, the finger is usually extended, where the angle between the joints is almost 0° (Fig. 4.1). When they tap, the angle between the joints changes (the finger becomes non-extended). The system uses the default Leap Motion SDK function to detect this change in the index finger to interpret it as a tap. Users naturally extend the finger after performing a tap, which makes this method reliable and easy to detect. We also considered using the downward velocity of the index finger to detect a tap. But in lab trials, this method was unreliable, resulting in many false positives due to the continuous movement of the hand when positioning the cursor.

- **Dwell.** With this method, users point at a target with the index finger then hold the current position for 800 ms to select the target. We picked the dwell time in a pilot study where 4 participants (2 female, 2 male, 30.3 years, *SD* = 3.1) selected six circular targets of 40 pixels in diameter, arranged in a circle of 200 pixels in diameter, using 4 dwell times (400, 600, 800, and 1000 ms) in a random order. In the pilot, 800 ms performed the best in terms of accuracy and user preference. This threshold falls within usable dwell times reported in the literature [161].

- **Pinch.** With this method, users point at a target with the index finger then pinch using the thumb and the index finger to select the target. It is detected based on the distance between the index finger and the thumb. When the distance is less than 0.05 mm, a pinch gesture is recognized. The 0.05 mm threshold was selected in lab trials, which revealed that the Leap Motion Controller usually returns values between 0.01 and 0.05 in pinching actions. Like *Tap*, users have to pinch and un-pinch to select a target. Continuous pinching actions are ignored by the system to reduce accidental selections.



(a) Ultraleap STRATOS Explore

(b) The complete experimental setup

Figure 4.3: (a) The haptics device with the metal cover used in the study, (b) Participants sat about 700 mm away front of a display. The Ultraleap device was placed on a small table closer to the users for comfortable gesturing actions.

4.5.1 Ultrasonic Haptic Feedback

The system uses the same haptic device as used in the previous Chapter, the Ultraleap STRATOS Explore [209] haptics board to provide mid-air haptic feedback (see Fig. 4.3a). The device is a phased array composed of 16 × 16 transducers that operate at a frequency of 40 kHz. The ultrasound waves produced by the transducers focus on a point within 600 mm above the device (for a detailed description of the board see Section 3.2.2). The experimental system tracks the hand and the fingers using a Leap Motion Controller, then aims ultrasound waves at the tip of the index finger. Due to the tracking limitation of the controller, discussed earlier, it limits interactions between 200 to 600 mm above the haptics device. Its 700 × 700 mm haptic interaction zone [209] was mapped to a 812.8 mm display using the SDKs default linear function. The haptics board comes with two metal and three acoustic fabric frame-mounted cover materials. The system uses a metal cover (Fig. 4.3a), however, we were unable to identify any effect of the covers on user performance or preference in lab trials. The default Ultraleap SDK includes several ultrasonic sensations and enables developers to create new ones. We designed two different types of sensations to provide mid-air feedback, described below.

- **Select.** This method provides feedback on selection tasks by applying 30 × 15 mm sensation on the fingertip for 400 ms. It simulates a Lissajous curve with the default parameters ($a = 3, b = 2$) in the Ultraleap SDK. The sensation was drawn at a frequency of 40 Hz. The dimension of the sensation was picked based on the average human fingertip [43], while the duration was picked in lab trials (50–800 ms) as it provided the most comfortable and noticeable mid-air haptics feedback. This feedback method is analogous to the press feedback method discussed in Section 3.2.2.
- **Hover & Select.** This method provides feedback on both hover (when the cursor is over a target) and selection tasks. It uses the same mechanism as the *Select* feedback (30 × 15 mm sensation via a Lissajous curve on the fingertip for 400 ms), but the hover sensation at 80% intensity and the select at 100% intensity (Fig. 4.4b). This feedback method is analogous to the touch and press feedback method discussed in Section 3.2.2.

4.6 Method

We conducted a Fitts' law experiment to investigate the performance of mid-air selection methods with and without ultrasonic haptic feedback.

4.6.1 Participants

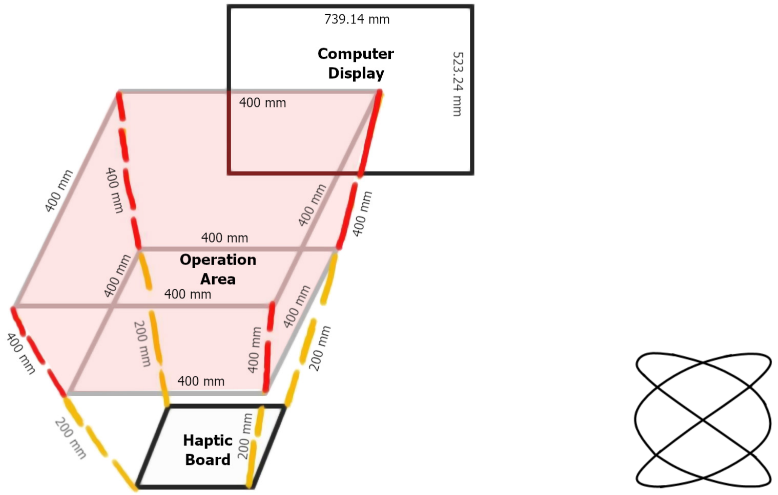
Twelve participants took part in the experiment (M = 30.5 years, SD = 4.7). None participated in the pilot study or the lab trials described earlier. Four identified as female, eight as male. All had university-level education. None were experienced with ultrasonic or other mid-air haptic devices. However, two had used mid-air selection methods at least once in VR. Ten self-identified as right-handed, one left-handed, and one ambidextrous. They received US $30 for participating in the study.

4.6.2 Apparatus

The system described in Section 4.5 was launched on an ASUS ROG GU501GM Gaming Laptop with Intel core i7 processor, 16 GB ram, NVDIA GeForce GTX 1060 graphics card, running on Windows 10 operating system. It was connected to an external display, HP Omen 32" gaming monitor at 2569 × 1440 pixels, where 1 pixel equals to 0.3 mm. The Fitts' law experimental protocol described in Section 4.4 was developed with Unity3D 2019.4.8f1.

4.6.3 Operation Area

The operation area was a 400 × 400 × 400 mm cubic area 200 mm above the haptic board (Fig. 4.4a). The system mapped finger movements in the x- and y-axes inside the area to x-y coor-



(a) (b)

Figure 4.4: (a) Operation area in the experiment setup (the red shaded area) and (b) Lissajous curve with parameters $a = 3$, $b = 2$.

dinates of the cursor on the computer display. Hence, the vertical operation plane was parallel to the display. When the cursor was over a target, the haptic board provided 30 × 15 mm sensation using a Lissajous curve on the fingertip for 400 ms. This fixed feedback area was selected based on multiple trials to provide comfortable feedback on the fingertip. The feedback area did not change based on the size of a target, instead the system dynamically changed feedback position based on movements in the x or y-axis, as appropriate. For example, when the user moved the finger along the the x- or y-axis but the cursor remained inside the target, the system adjusted feedback position to provide seamless feedback on the fingertip. Movements along the z-axis were ignored; that is, the cursor did not change position based on movements in the z-axis. However, when the velocity of the movement exceeded 100 mm/s, a *Push* gesture was registered. Movements in the z-axis were also used to adjust the feedback position. For example, when the user moved the finger along the z-axis as the cursor remained on a target, the system dynamically changed feedback position along the z-axis to provide seamless feedback on the fingertip.

4.6.4 Procedure

The study started with a researcher explaining the research and demonstrating the system to the participants. They then signed an informed consent form and completed a short demographics questionnaire. They sat about 700 mm from the display with the haptics board placed on a small table (Fig. 4.3b) to provide a comfortable and reliable gesturing position (i.e., 200 mm above the haptic board). At this distance, a target of 100 pixels presents a visual angle of 2.46°.

Participants were instructed to adjust the chair to a comfortable position if needed. They then took part in a 10-minute training block, where they selected 11 circular targets of 40 pixels in diameter, arranged in a circle of 200 pixels in diameter, with the four mid-air gestures in a random order. The main study started after that, where participants selected targets using the four selection methods augmented with the three feedback methods in a counterbalanced order using a Latin square. They were instructed to select the targets as quickly and accurately as possible without compromising comfort. We enforced a 2-minute break after each three sequences and a 5-minute break after each condition, to avoid fatigue. Participants could also request breaks at any point or extend the duration of the mandatory breaks, when needed. After the completion of all conditions, participants completed the NASA-TLX questionnaire [79] to rate the perceived workload of *only* the four selection methods. The questionnaire was not used to rate all conditions to keep the duration of the study within 60–90 minutes (Section 4.7.5). Participants also completed a custom questionnaire to rate the examined haptic feedback methods' effects on their performance and preference.

4.6.4.1 Safety Measures for COVID-19

All researchers involved in this study were fully vaccinated for COVID-19. All participants were pre-screened for COVID-19 symptoms during the recruitment process by a researcher, and on the day of the experiment by the host institute. Both the researcher and the participants wore face coverings and sanitized their hands before a study session. The researcher also maintained a three-foot distance from the participants at all times. All study devices and furniture were disinfected before and after each study session. This protocol was reviewed and approved by the Institutional Review Board (IRB).

4.6.5 Design

The experiment was a $4 \times 3 \times 3 \times 3$ within-subjects design. The independent variables and levels were as follows:

- Selection method (*Push*, *Tap*, *Dwell*, *Pinch*) counterbalanced
- Haptic feedback (*None*, *Select*, *Hover & Select*) counterbalanced
- Amplitude (80, 360, 640 pixels)
- Width (25, 50, 75 pixels)

There were 11 trials per sequence. The three amplitudes were selected based on the capability of the haptic board and the motion sensor since they are not reliable with amplitudes outside the 80–640 pixels range. Likewise, the three widths were selected based on the smallest width recommended by the manufacturer (25 pixels) [208], while targets with widths over 75 pixels are unrealistic.

4.6.5.1 Performance Metrics

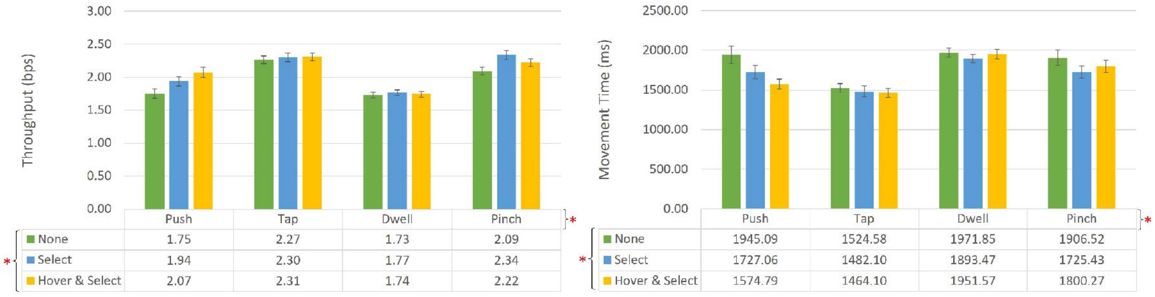
The dependent variables in the experiment were throughput (TP) and movement time (MT), as described in Section 4.4, as well as target re-entries (TRE) and error rate (ER). Target re-entries represent the total number of times the cursor re-entered the targets in a trial after having entered them once (count/trial). Error rate signifies the average percentage of incorrect target selections per trial (%), where users performed a selection gesture outside the target.

4.6.5.2 Graphical Feedback

The experimental software provided graphical feedback when the cursor was over a target by changing the color from red to blue. This feedback was included based on a pilot study, where some participants had difficulty selecting small targets in the no-haptic-feedback conditions as they could not always tell if the cursor is over the target or at the edge. Because this feedback was provided in all conditions, it is not a confounding variable in the study design. Instead, since "changes in object coloring" is the most common type of feedback provided for target selection with mid-air gestures [215, 117], we argue that this decision increased the external validity of the work.

4.7 Results

A complete study session took about two hours to complete, including demonstration, questionnaires, and breaks. A Shapiro-Wilk test revealed that the response variable residuals were normally distributed. A Mauchly's test indicated that the variances of populations were equal. Hence, we used a repeated-measures ANOVA for all quantitative within-subjects factors (Section 4.6.5). We report effect size for all statistically significant results. Eta-squared uses the Cohen's [37] interpretation where $\eta^2 = 0.001$ constitutes a small, 0.5 constitutes a medium, and 0.1 constitutes a large effect. There were in total 1,296 observations, none were excluded from the analysis as outliers.



(a) Throughput (bps)

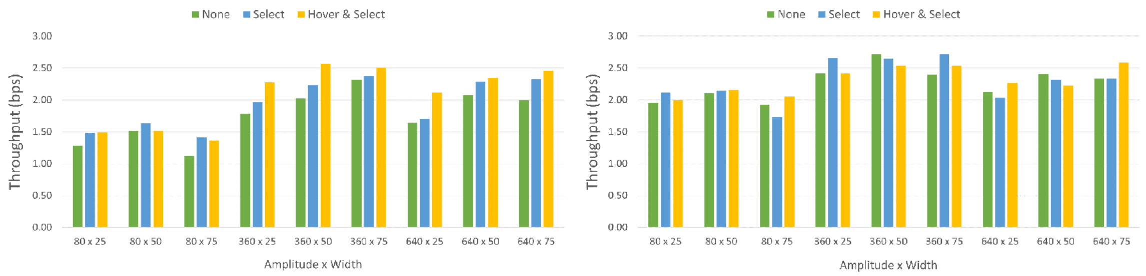
(b) Movement time (ms)

Figure 4.5: Average throughput and movement time by selection method and haptic feedback. Error bars represent ±1 standard error. Significant main effects are highlighted with red asterisks.

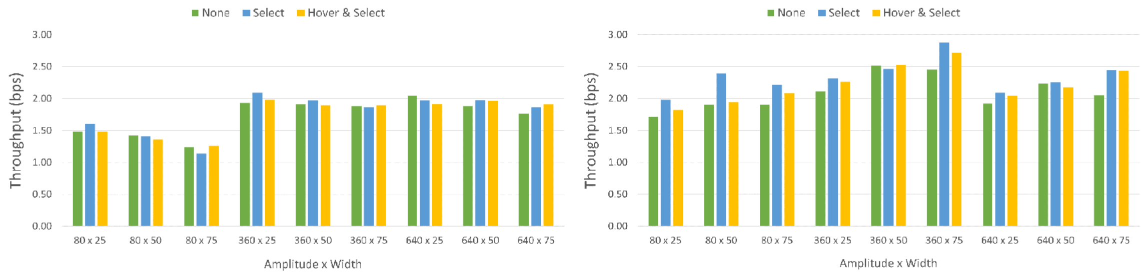
4.7.1 Throughput

The grand mean for throughput was 2.04 bps. The breakdown by selection method and haptic feedback is presented in Fig. 4.5a. By selection method, the highest throughput was 2.29 bps for *Tap*, followed by 2.21 bps (*Pinch*), 1.92 bps (*Push*), and 1.75 bps (*Dwell*). The differences were statistically significant ($F_{3,33} = 21.08, p < .0001, \eta^2 = .21$). By haptic feedback, the highest throughput was 2.09 bps for the *Select* and *Hover & Select*, followed by 1.96 bps for the *None*. The differences were statistically significant ($F_{2,22} = 5.80, p < .01, \eta^2 = .02$). *Pinch* with *Select* yielded the highest throughput (2.34 bps). However, the selection method × haptic feedback interaction effect was not statistically significant ($F_{6,66} = 1.64, p > .05$).

The breakdown by amplitude and width is presented in Fig. 4.6. By amplitude, the highest throughput was 2.30 bps for 360 pixels, followed by 2.13 bps (640 pixels) and 1.71 bps (80 pixels). The differences were statistically significant ($F_{2,22} = 67.17, p < .0001, \eta^2 = .24$). By width, the highest throughput was 2.10 bps for 50 pixels, followed by 2.07 bps (75 pixels) and 1.96 bps (25 pixels). The differences were also statistically significant ($F_{2,22} = 5.31, p < .05, \eta^2 = .01$). There was also an amplitude × width interaction effect ($F_{4,44} = 6.09, p < .001$). 360 × 75 pixels yielded the highest throughput (2.38 bps).



(a) Push (b) Tap

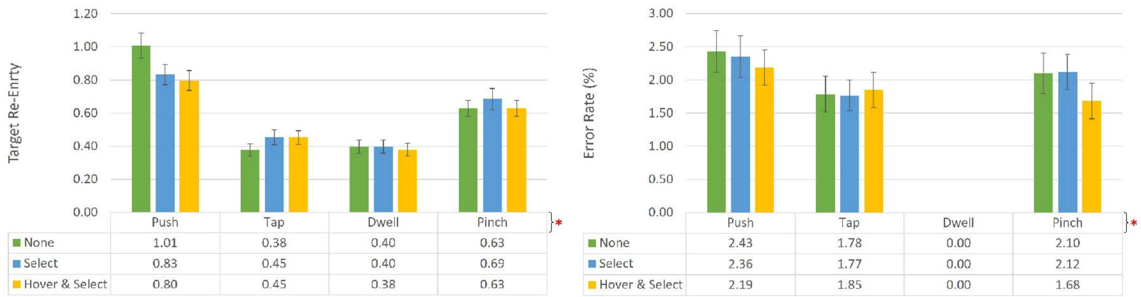


(c) Dwell (d) Pinch

Figure 4.6: Average throughput (bps) for the four examined mid-air gestures by amplitude × width and haptic feedback.

4.7.2 Movement Time

The grand mean for movement time was 1747 ms. The breakdown by selection method and haptic feedback is presented in Fig. 4.5b. *Tap* was the fastest of all selection methods (1490 ms), followed by *Push* (1749 ms), *Pinch* (1810 ms), and *Dwell* (19396 ms). The differences were statistically significant ($F_{3,33} = 8.43, p < .0005, \eta^2 = .06$). By haptic feedback, *Hover & Select* was the fastest (1698 ms), followed by *Select* (1707 ms) and *None* (1837 ms). The differences were statistically significant ($F_{2,22} = 5.54, p < .05, \eta^2 = .01$). However, the selection method × haptic feedback interaction effect was not statistically significant ($F_{6,66} = 1.34, p > .05$). A Tukey-Kramer multiple-comparisons test revealed that *Push* and *Tap* + *Hover & Select* were significantly faster than the other methods (∼20% faster).



(a) Target re-entry (count/trial)

(b) Error rate (%)

Figure 4.7: Average target re-entry and error rate by selection method and haptic feedback. Error bars represent ±1 standard error. Significant main effects are highlighted with red asterisks.

4.7.3 Target Re-Entries

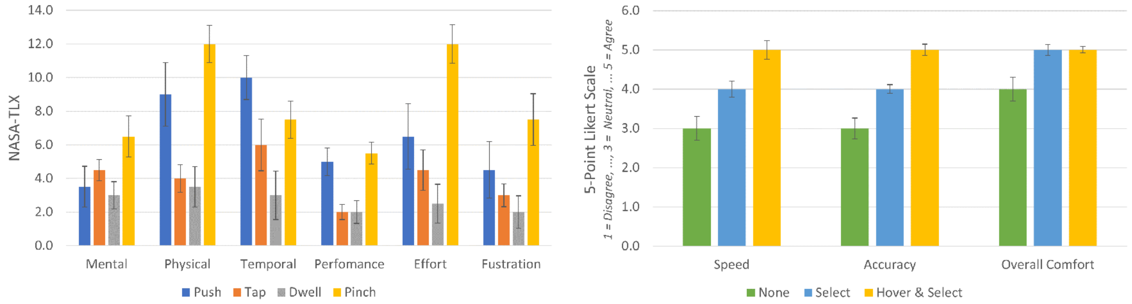
The grand mean for target re-entries was 0.59 count/trial. The breakdown by selection method and haptic feedback is presented in Fig. 4.7a. By selection method, *Dwell* required the least number of target re-entries (0.39 count/trial), followed by *Tap* (0.43 count/trial), *Pinch* (0.65 count/trial), and *Push* (0.88 count/trial). The differences were statistically significant ($F_{3,33} = 16.46, p < .0001, \eta^2 = .05$). By haptic feedback, *Hover & Select* required the least number of target re-entries (0.56 count/trial), followed by *Select* (0.59 count/trial) and *None* (0.60 count/trial). The differences were not statistically significant ($F_{2,22} = 0.30, ns$). There was also no significant effect of selection method × haptic feedback ($F_{6,66} = 1.18, p > .05$). However, a Tukey-Kramer multiple-comparison test revealed that *Tap* and *Dwell* caused significantly lower target re-entries than *Push* and *Pinch* ($\sim$50% lower).

4.7.4 Error Rate

The grand mean for error rate was 2.06%. The breakdown by selection method and haptic feedback is presented in Fig. 4.7b. By selection method, *Dwell* was the most accurate with a 0% error rate, followed by *Tap* (1.77%), *Pinch* (1.99%), and *Push* (2.32%). The differences were statistically significant ($F_{3,33} = 25.33, p < .0001, \eta^2 = .05$). By haptic feedback, *Hover & Select* was the most accurate (1.32%), followed by *Select* (1.56%) and *None* (1.57%). The differences were not statistically significant ($F_{2,22} = 1.28, p > .05$). There was also no significant effect of selection method × haptic feedback ($F_{6,66} = 1.11, p > .05$). A Tukey-Kramer multiple-comparison test identified *Push* to be significantly more error-prone and *Dwell* to be significantly more accurate than the other methods. The performance of *Tap* and *Pinch* were comparable (1.8–1.9% error rate).

4.7.5 User Feedback

Participants completed two questionnaires upon the completion of the conditions. A NASA-TLX questionnaire [79] to rate the perceived workload of the selection methods and a custom questionnaire to rate the perceived effects of the feedback methods on their performance (speed and accuracy) and physical and mental comfort on a 5-point Likert scale. We did not use the NASA-TLX questionnaire for all ($4 \times 3 = 12$) conditions to limit the duration of the study. Besides, we argue that the overall mental and physical workload of the selection methods and the perceived effects of the feedback methods on user performance is more relevant to this work than the perceived workload of the feedback methods. We used a Friedman test to compare user ratings of the examined selection and haptic feedback methods.



(a) NASA-TLX questionnaire

(b) Usability questionnaire

Figure 4.8: Median perceived workload of the examined selection methods and perceived effects of the examined feedback methods on user performance and overall comfort (physical and cognitive). Error bars represent ±1 standard error.

4.7.5.1 Perceived Workload of the Selection Methods

A Friedman test identified a significant effect of selection method on mental demand ($\chi^2 = 10.32, df = 3, p < .05$)), physical demand ($\chi^2 = 16.18, df = 3, p < .05$)), performance ($\chi^2 = 11.24, df = 3, p < .05$)), effort ($\chi^2 = 11.25, df = 3, p < .05$)), and frustration ($\chi^2 = 15.32, df = 3, p < .005$)). However, no significant effect was identified on temporal demand ($\chi^2 = 5.64, df = 3, p = .13$). Fig. 4.8a presents median user ratings of the four selection methods.

4.7.5.2 Perceived Effects of the Feedback Methods

A Friedman test identified a significant effect of feedback method on speed ($\chi^2 = 11.42, df = 2, p < .005$)), accuracy ($\chi^2 = 19.46, df = 2, p < .0001$)), and overall comfort ($\chi^2 = 8.67, df = 2, p < .05$)). Fig. 4.8b presents median user ratings of the three feedback methods.

4.8 Discussion

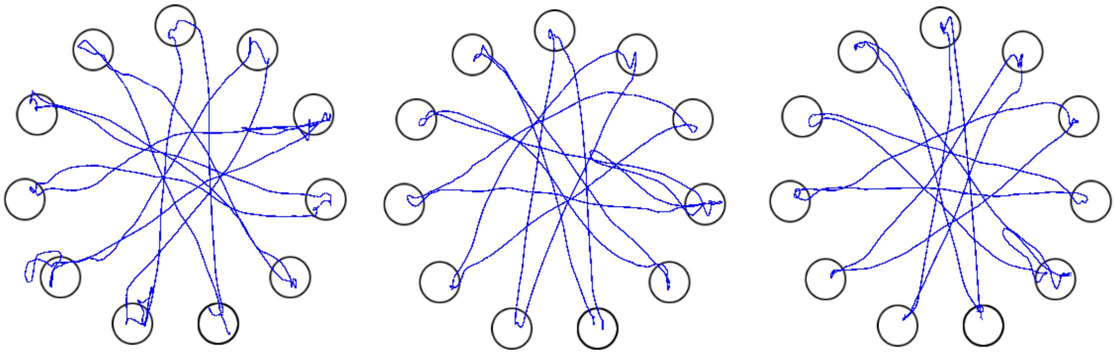
Tap and *Pinch* outperformed *Push* and *Dwell* in terms of throughput (∼20% higher throughput, large effect size). A Tukey-Kramer multiple-comparison test identified these two groups to be significantly different. *Tap* was also significantly faster than the other methods (Fig. 4.5b). *Dwell* was the slowest of all methods, as expected, since users had to wait for an 800 ms timeout period to select a target. Target amplitude and width influenced the selection methods in accordance to the Fitts' law (large and small effect sizes, respectively, see Fig. 4.6).

Haptic feedback improved the performance of all methods (small effect size). A Tukey-Kramer multiple-comparison test identified the methods with haptic feedback to be significantly faster and more effective than without feedback. In particular, the performance of *Push* + *Hover & Select* and *Pinch* + *Select* elevated closer to *Tap* (Fig. 4.5a). A Tukey-Kramer multiple-comparison test identified this improvement to be statistically significant. It is important to note that haptic feedback improved the performance of all methods despite all providing graphical feedback on collision to aid target selection (Section 4.6.5.2). This suggests that graphical feedback alone is not effective enough to facilitate mid-air gestural interaction.

We speculate, two factors contributed towards *Tap*'s superior performance. First, based on user responses, performing the gesture did not demand as much physical and cognitive effort as most other methods (Fig. 4.8a). Second, it did not require a high level of spatial awareness since there was no restriction on how much they could bend the finger, which reduced the total number of re-entries (Fig. 4.7a), improving its overall performance. A case in point, *Push* without feedback was significantly slower than *Tap* despite being a visually similar gesture (Fig. 4.5b). A Tukey-Kramer multiple-comparison test revealed that it resulted in significantly more target re-entries than *Tap*, which increased the physical and cognitive effort (Fig. 4.8a) and affected the overall performance (Fig. 4.5). Its 1.01 target re-entry rate suggests that participants frequently overshot the targets (Fig. 4.7a), presumably due to the lack of special reference. With *Push*, participants moved the index finger forward, like pressing a virtual button in the 3D space. Due to the human physiology, this also moved the hand. Without spatial references, it was difficult for the participants to estimate how far they should move the finger to select a target, often moving it too much, which the system interpreted as a pointing action rather than a selection action. This phenomenon has been observed in other 3D interfaces. [83] argued that *"to perform a [3D] task, the user's perceptual system needs something to refer to, something to experience"* and *"using a spatial reference [...] is one way to provide this perceptual experience"*. Consequently, target re-entries reduced by 18% and 21%, and throughput increased by 11% and 18%, when *Push* was augmented with *Select* and *Hover & Select* feedback methods, respectively, because the feedback provided the participants with a reference to which they can adjust the finger. Fig. 4.9 illustrates cursor traces from a random participant for *Push* with the three feedback conditions, where one can see that *Push* without haptic feedback caused multiple target re-entries but none when augmented with a haptic feedback method.

Prior work reported that the performance of 3D interaction methods can improve substantially with practice when spatial references are provided. In an early work, [10] reported that providing users with spatial reference in 3D selection task can make a *"consciously calculated activity"* to a *"simple and effortless process"*. Hence, the performance of *Push* with haptic feedback can improve further over time. Relevantly, target re-entries for *Tap* and *Dwell*, which do not rely heavily on spatial awareness, are much lower than the other methods (Fig. 4.7a). A Tukey-Kramer multiple-comparison test revealed that *Dwell* was significantly more accurate (0% error rate) than the other methods, while *Push* was significantly less accurate than *Tap* and *Pinch*. This is not surprising since with *Dwell* the users did not have to perform any additional action but holding the current finger position for 800 ms. *Tap* was the second most accurate, presumably due to the reasons discussed earlier.

Participants found *Dwell* the least physically and cognitively demanding (Fig. 4.8a), regardless of it being significantly slower than the other methods. We speculate this is because *Dwell* did not require users to rely on their spatial awareness or perform a gesture that is different than the one used for moving the cursor. As a result, its performance did not improve much with haptic



(a) *Push* with no feedback (b) *Push* with *Select* (c) *Push* with *Hover & Select*

Figure 4.9: Cursor trace examples for *Push* ($A = 360$, $W = 50$ pixels) with the three feedback conditions.

feedback (Fig. 4.5). *Tap* was the second least physically and cognitively demanding. Interestingly, participants found *Pinch* to be more physically demanding, effortful, and frustrating than the other gestures despite it being more effective than *Push* and *Dwell* in target selection. This could be either because *Pinch* was the only gesture that required the use of two fingers or since it was misrecognized a number of times during the study (about 1.5% of all instances). We discuss this further in Section 4.8.1.

All participants (N = 12) felt that haptic feedback improved their selection accuracy and the overall physical and cognitive comfort (Fig. 4.8b). Likewise, most participants (N = 10) felt that haptic feedback improved their selection speed, while the remaining participants (N = 2) were neutral about it.

4.8.1 Technical Issues

A few technical issues were recorded during the study. First, the Leap Motion Controller seldom stopped tracking the hand (0.01% of all cases). In such cases, we restarted the affected sequence. Second, in general, the system was able to recognize the mid-air gestures with about 100% accuracy, however, on a few occasions (about 1.5% of all cases), it was unable to recognize *Pinch*, in which case, participants performed the gesture again. Finally, the haptic feedback methods were not as effective when the hand was moving fast. However, our observation suggests that it did not affect performance since participants usually slowed down when the finger was closer to the target.

4.8.2 Generalizability in Different Postures

In the study, participants were in a seated position and selected targets at shoulder level with a bent or extended arm (Fig. 4.3b). One limitation of the work is it did not explore other possible positions (i.e., standing) and postures (i.e., interaction plane between the shoulder and the waist, at or below the waist, and with a bent arm). We speculate that the performance differences between the gestures will be comparable in different positions and postures in limited use. However, it is possible that the performance of some gestures will be affected more than the others in extended use due to increased "endurance", which is defined as *"the amount of time a muscle can maintain a given contraction level before needing rest"* [82]. Research showed that selecting targets at shoulder level with an extended arm consumes more endurance than targets between the shoulder and the waist [82]. The biomechanics of the upper limbs also suggest that selecting targets below the waist (like on a kiosk) is likely to consume the least endurance as it does not require extending the arm up, thus the arm remains closer to its resting position [138, 64]. Performing the gestures standing up, in contrast, can consume more endurance since users cannot rest their arms on the lap between the tasks. Further investigation is needed in this direction to fully understand the effects of different positions, postures, and gestures on endurance, and to find a definite answer to whether the findings of this work are generalizable to all positions or postures.

4.9 Design Recommendations

Drawing on the findings of this work, we made recommendations for picking the most appropriate mid-air selection method based on the type of tasks, performance priorities, and technological limitations, summarized in Table 4.2. Although aiming for the top speed and accuracy in all interactive systems may appear desirable, it is neither necessary nor possible or cost-effective in all scenarios. For instance, in a VR game where players score points by selecting big incoming targets as fast as they can (e.g., fruit slice or slashing games), aiming for a comfortable and fast gesture that supports repetitive performance is sufficient considering the target size and task frequency. Likewise, in scenarios where accuracy is most preferred than speed and the task is not repetitive (e.g., entering PIN on an ATM machine), a more accurate gesture is sufficient (since speed and comfort in non-repetitive tasks are not vital). Repetitive tasks are performed repeatedly for a longer period, like the fruit slice game or in text entry. Non-repetitive tasks are performed occasionally, such as pressing a virtual button to exit a window, open a file, or to enter a few characters (e.g., PIN). Hence, the methods appropriate for repetitive actions could be used for non-repetitive actions as well, but not vice versa. We recommend using methods with high accuracy rates, especially for repetitive tasks, since users tend to get impatient and frustrated with error-prone gesture-based methods and deem them unusable when the error rate is over 3% [6]. However, all methods examined here yielded high accuracy (below 2.5% error rates). Note that the table reports comfort in limited use (within an hour) and does not account for fatigue in extended use.

4.10 Conclusion

We conducted a Fitts' law experiment to compare the performance of four mid-air selection methods: *Push*, *Tap*, *Dwell*, and *Pinch*, with and without two different types of ultrasonic haptic feedback: *Select*, *Hover & Select*. Results identified *Tap* as the fastest, the most accurate, and one of the least physically and cognitively demanding selection methods. *Pinch* performed well in terms of speed, but yielded a much higher error rate and perceived workload. *Dwell* was the slowest of all methods by design, but interestingly, the most accurate and the least physically and cognitively demanding. Both haptic feedback methods improved the performance of the selection methods, presumably by increasing users' spatial awareness. Particularly, the performance of *Push*, which relies on users' spatial awareness, improved substantially with haptic feedback, making it compara-

Table 4.2: Recommendations for picking the most appropriate mid-air selection method based on the type of tasks (repetitive or not repetitive actions), performance priorities (top, moderate, low), and technological limitations (availability of haptic feedback). Comfort signifies perceived workload. "Bps" indicates throughput in bits/second (only throughputs of the best performed haptic feedback are reported). The highlighted fields signify the best performed methods.

Haptic Feedback (Recommended)	**Priority**				**Method**	**Bps**
	Repetitions	**Accuracy**	**Speed**	**Comfort**		
Not Available	Low	Moderate	Top	Low	*Pinch*	2.09
	Low	Top	Low	Top	*Dwell*	1.73
	Moderate	Moderate	Moderate	Moderate	*Push*	1.75
	Top	Top	Top	Top	*Tap*	2.27
Available	Low	Moderate	Top	Low	*Pinch*	2.34
	Low	Top	Low	Top	*Dwell*	1.77
	Top	Moderate	Top	Top	*Push*	2.07
	Top	Top	Top	Top	*Tap*	2.31

ble to *Tap*. Besides, participants perceived the selection methods as faster, more accurate, and more physically and cognitively comfortable with the haptic feedback methods. These findings further validate our conclusions in Chapter 3, establishing the effectiveness of ultrasonic haptic feedback for enhancing mid-air gesture interactions.

Chapter 5

Gesture Typing with a Digital Thimble

So far, our efforts to address input and interaction challenges in VR have been based on existing technologies. Despite these efforts, ongoing limitations have highlighted the need for innovative solutions, leading us to explore custom hardware development. In this Chapter, we introduce a new technique called Shapeshifter, designed to facilitate free-hand gesture typing [118, 243] in VR on any opaque, diffusely reflective surface, including the human body (see Fig. 5.1). This method employs a custom digital thimble worn on the user's index finger. The thimble is equipped with an optical sensor to track the finger's position and a pressure sensor to detect touch contact force. By integrating these technologies, Shapeshifter aims to significantly enhance text entry capabilities in the virtual environment, offering a more versatile and intuitive typing experience.

Most existing text entry techniques for VR use extramural devices that are either placed on a table (e.g., physical keyboards [70, 181]) or held with one or both hands (e.g., game controllers [239, 200] and smartphones [114, 32]). Because users cannot see these extramural devices when wearing a head-mounted display (HMD), these techniques usually display their virtual representations in the virtual world and provide continuous graphical and auditory feedback to keep them informed about the current state of the system. These techniques are not always practical for VR since they require a fixed flat surface (i.e., a table), which compromises the mobility of users, forcing them to perform only the tasks that can be performed when stationary. Holding extramural devices, on the other hand, restricts their ability to use their hands to perform other tasks. Locating and activating these devices is also difficult when wearing an HMD and can divert users' mind from the task at hand. Techniques that use digital gloves and other wearable devices are conspicuous and uncomfortable [228, 110, 98]. As discussed and explored in Chapter 2 some techniques track the fingers to enable entering text by typing on a virtual keyboard on a flat surface or mid-air [200, 99]. Some of these techniques, however, require users to look down at the hands for the HMD to track the fingers, which is unnatural. Some techniques also use new keyboard layouts optimized for VR, which are not only difficult to learn and use but also rely heavily on decoders, which makes entering out-of-vocabulary (OOV) words difficult, and often impossible.

Gesture typing can significantly improve typing speed and accuracy compared to traditional methods, especially for mobile devices. Yet, in VR, it remains slow, error-prone, cumbersome, and difficult to learn. Our goal for this work is to develop a method for improving gesture typing in VR that emphasizes natural interaction and ease of use. Thus in this Chapter, we present Shapeshifter a gesture typing technique using a force-based digital thimble on any opaque diffusely reflective surface. Shapeshifter also supports character-level entry (entering one character at a time) for abbreviations and OOV words by applying and releasing extra force on each key. The contribution of this work is thus twofold: the development of a digital thimble that can be used as an independent input and interaction device in VR and the development of a technique that enables users to enter text by drawing gestures with varying contact force.

The remainder of this Chapter is structured as follows. First, we review related work. Next, we discuss the development of the thimble and Shapeshifter technique. We then detail the long-term pilot study and the simulation study. Following this, we present and discuss the results. Finally, we conclude by highlighting key findings and limitations.

5.1 Related Work

5.1.1 Text Entry in Virtual Reality

In Chapter 2.1 we summarized current methods for typing in VR. Most of these methods are character-level text input methods. This means that users enter words one character at a time. On the other hand, gesture typing (also known as swipe or glide typing) is a popular word-level text input method on touchscreen devices and offers a potential alternative. With gesture typing, users trace a continuous path across the virtual Qwerty, connecting the letters of the intended [118]. Research has shown that this method can significantly improve typing speed and accuracy compared to traditional character-based input [171, 237]. Further research has focused on the development of gesture decoding algorithms to optimize word prediction and error correction [171], as well as utilizing human motor control models to understand gesture typing movements and optimize the user experience.

5.1.2 Gesture Typing in Virtual Reality

Several techniques enable word-level text entry in VR with gesture typing. A common approach is to use controllers. With this technique, users press a button on the controller, trace the path of a desired word on a floating virtual Qwerty, then release the button to enter the word [32, 235]. There are also some free-hand gesture typing techniques. Gupta et al [75] developed a digital ring with motion sensors, with which users first rotate the hand to point the cursor to the first letter of the intended word, click a button on the ring to start gesturing, then press the button again to enter the respective word. [99] attached a Leap Motion controller to the headset to track the fingers. With this technique, users perform the gestures while pinching the finger. Releasing the pinch enters the respective word. The widespread use of smartphones has encouraged gesture typing on smartphones to enter text in VR [32, 81]. Some techniques also enable gesture typing with head movements [239], where users point to the first letter of a word, trace the path of the word with head movements while holding down a controller button, then release the button to enter the respective word. A similar technique [231] replaces the controller button with a virtual one, on which users dwell for 400 ms to start gesturing. While some of these techniques can be relatively fast, they require the use of the hands, which limits what users can do in the virtual world, breaks immersion, or causes severe cognitive and physical strain over time. Gesture typing has also been explored in augmented reality [230], which is outside the context of this work. Table 5.1 presents the performance of gesture typing

Figure 5.1: Two users using Shapeshifter to gesture type in VR in four scenarios: (a) on a desk when sitting down, (b) on the lap when sitting down, (c) on the back of the hand when standing up, and (d) on the palm when standing up. Both users are wearing the digital thimble introduced in this paper for gesture detection.

techniques for VR. We provided a comprehensive review of existing text entry techniques for VR in a survey [54].

Table 5.1: Performance of text entry techniques exploiting gesture typing in VR. This table presents the highest reported performance when multiple settings or conditions were explored. Here, OOV represents the support for out-of-vocabulary word entry, and WPM and ER represent the words per minute and error rate performance metrics, respectively. The values marked with τ signify erroneous keystroke error rate [4]. α means the technique worked on a circular keyboard. δ means Shapeshifter results simulated for Novice Users.

Technique	Technology	OOV	WPM	ER%	Experimental Task
Freehand [99]	Camera	No	NA	NA	Text transcription
Controller [32]	Controller	Yes	16.4	0.16^{τ}	Text transcription
Controller [235]	Controller	No	21.0	26.0	Text transcription
Smartphone [32]	Touchscreen	Yes	9.6	0.23^{τ}	Text transcription
Smartphone [81]	Touchscreen	Yes	13.15	0.16^{τ}	Text transcription
Hand Rotation [75]	Inertial sensor	Yes	14.8	9.40	Text transcription
Head & Controller[239]	HMD + controller	No	24.7	5.80	Text transcription
Head$^{\alpha}$[231]	HMD tracking	No	6.32	5.50	Text transcription
Head [231]	HMD tracking	No	6.32	7.10	Text transcription
Shapeshifter	Digital thimble	Yes	8–11	2–4.6	Text composition
Shapeshifter, Simulated$^{\delta}$	Digital thimble	Yes	27.3	0	Text Transcription

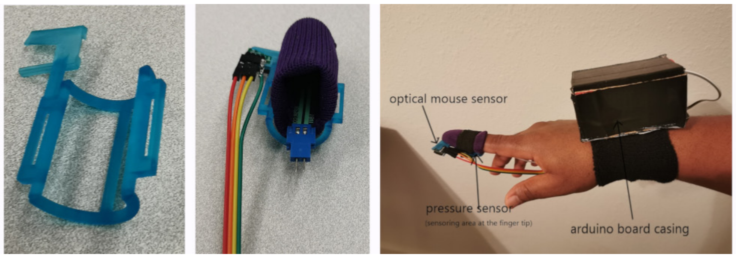


Figure 5.2: The custom digital thimble. From left: the 3D printed frame to hold the optical sensor, the thimble with the optical sensor on the side and the pressure sensor inside the tip of the thimble, and the complete device with the sensors connected to an Arduino Uno Rev3 microcontroller placed inside a cardboard case worn on the wrist.

5.2 A Digital Thimble

We developed a digital thimble to track the index finger in VR. It is made from fabric for comfort and to reduce weight (Fig. 5.2). For tracking the finger's movements, we have integrated an optical mouse sensor into the thimble. Optical mouse sensors typically employ either a light-emitting diode (LED) or a laser light source to illuminate the surface below the mouse. As the thimble is moved across the surface, the sensor captures a series of consecutive images of that surface and applies digital signal processing techniques to analyze them. By comparing these images, the sensor can precisely compute both the distance and direction of the thimble's movement. The resulting data is then transmitted to the computer, where it is further processed and used to control the on-screen cursor.

The digital thimble tracks the finger using an FCT 3065-XY Optical Sensor attached to the side using a 3D-printed frame. This sensor was collected from a RivenAn Mini 2.4GHz USB Wireless Finger Rings Optical Mouse to reappropriate its circuit board for the thimble (Fig.5.3). Its 1,200 dpi is also ideal for tracking gestures since it affords users more precision and control. The frame was designed to maintain the recommended 2–2.55 mm distance between the sensor and the fingertip for effective sensing [229]. The wires connecting the optical sensor and the circuit board were also kept as short as possible since longer wires compromise sensing accuracy. The thimble detects touch and contact force using a Force Sensing Resistors (FSR) 400 series pressure sensor. It is attached

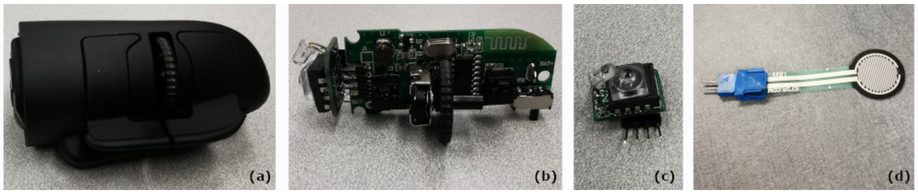
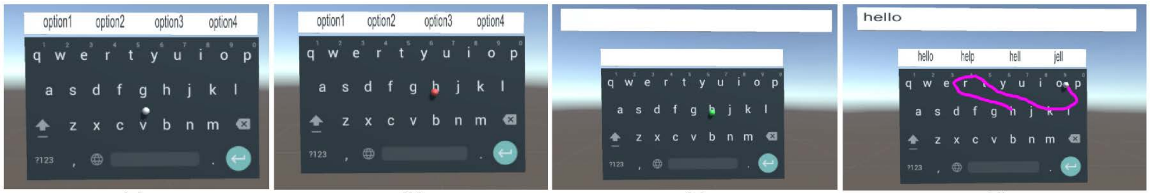


Figure 5.3: The optical and pressure sensors used in the digital thimble: (a) a RivenAn Mini 2.4GHz USB Wireless Finger Ring Optical Mouse, (b) the mouse without casing, (c) the optical sensor from the mouse, and (d) a Force Sensing Resistors (FSR) 400 series pressure sensor. The images are not to the scale.

inside the tip of the thimble, coated with silicone so that it does not irritate the finger. The FSR is connected to a Arduino Uno Rev3 microcontroller placed inside a cardboard case worn on the wrist (Fig. 5.2). The sensor has a 12.7 mm diameter with a 20 mm^2 sensing area (Fig. 5.3) and a sensing range between 100 g and 10 kg, which is sufficient for detecting touch. Besides, its circular shape is convenient for measuring force from the fingertip. The resistance of the FSR varies as the force on the sensor changes. When no force is applied, the resistance is slightly larger than 1 MΩ. The harder the sensor is pressed the lower the resistance. Specifically, the FSR and a static resistor form a voltage divider for the analog-to-digital converter of the microcontroller to read a variable voltage and translate it to force values. We considered different technologies for tracking the finger, including depth/RGB cameras, magnetism, gyroscope, and infrared sensors (e.g., [106, 236, 160, 183, 202]). But we decided on using an optical sensor due to its availability and affordability. Optical sensors are commonly used in mice as they work on a wide range of surfaces and scenarios [153, 12, 236, 131]. Since the sensor does not rely on a head-mounted display for finger tracking, the thimble can also be used for interaction with other computer systems.



(a) (b) (c) (d)

Figure 5.4: Shapeshifter looks and feels like the default Google Android keyboard. To enter text with Shapeshifter, the user (a) touches a surface (grey cursor), (b) applies extra force to activate the cursor (red cursor), (c) positions the cursor over the first letter of the intended word and applies extra force to start a gesture (green cursor), and (d) completes the gesture maintaining extra force, then reduces force to automatically enter the word associated with the gesture (pick tracing). Shapeshifter enables users to enter multiple words by switching between regular and extra force, without ever lifting the finger. Lifting the finger off the surface deactivates the cursor. The keyboard displays a suggestion bar with the most probable alternative words. The user can replace the output word with a suggested word by applying extra force upon moving the cursor over the suggested word, like pressing a button.

5.3 Shapeshifter

We designed Shapeshifter, a method for free-hand gesture typing in VR using the digital thimble. To use Shapeshifter, users wear the thimble on the index finger and perform gestures on any opaque diffusely reflective surface, including the human body , by varying contact force. To draw a gesture or to perform a thimble-based interaction, users first activate tracking by applying extra contact force. Hence, users can perform other tasks while wearing the thimble without worrying about accidental interactions.

The digital thimble controls a 2D cursor in the virtual world. The cursor has three modes: *inactive*, *active*, and *gesturing*. These modes are visually distinguished by the colors grey, red, and green, respectively. Touching a surface with the thimble displays the inactive cursor at the center of a virtual keyboard (Fig. 5.4). To activate the cursor, users increase and decrease contact force once as if they are pressing down and releasing an invisible button. Once activated, moving the finger moves the cursor over the keyboard. To switch to the gesturing mode, users apply and maintain extra force, then gesture type by connecting the letters in the sequence in which they appear in the intended word. Releasing extra force completes a gesture and enters the most probable word associated with the gesture. Expert users, therefore, can enter multiple words by switching between regular and extra force, without ever lifting their fingers. The keyboard provides visual feedback on gesture typing by tracing finger movements in pink. Moving the finger without applying extra force moves the cursor but does not select the items underneath. Users can also enter one character at a time, like entering text with a conventional keyboard, by increasing and decreasing contact force once like pressing a button. This feature is particularly useful when entering out-of-vocabulary (OOV) words.

The digital thimble detects a touch when the contact force is above 10 g, activates the cursor when the contact force increases and decreases between 100 and 400 g, and registers a gesture when the contact force is over 400 g. These values were selected based on a pilot study (N = 5, M = 29 years) that revealed that usual contact forces are almost always over 10 g, regular touch interactions are usually between 100 and 400 g, and the 400 g threshold is the most reliable to distinguish between regular and extra force without inducing physical or cognitive stress.

Similar to the default Google Android keyboard [123], Shapeshifter includes a suggestion bar to display the most probable input words (Fig 5.4). Users can replace an entered word with a suggested word by applying and releasing extra force on the suggestion bar. The suggestion bar can also auto-complete and auto-correct words in character-level text entry. Applying extra force on the Backspace key deletes the last entry, that is, the last word in word-level text entry and the last character in character-level text entry. Table 5.2 presents the actions required to enter text with Shapeshifter.

We developed a custom keyboard resembling the Google keyboard [123]. For this, we used Unity3D 2017.14.17 (Fig. 5.4). It recognizes the gestures drawn over it using a custom algorithm developed based on prior works [118, 239, 211]. It compares the shape and the location of each gesture drawn with gesture templates for 10,000 most common words in the English language [103]. This lexicon is sufficient to cover daily use as the 7,000 most common lemmas make up about 90% of spoken English [103]. The gesture template for a word is programmatically generated as straight lines connecting the center of each key in the sequence in which they form the word. To compare a template to a gesture, both are re-sampled at 50 equidistant points. Prior works found this number to be adequate for comparing patterns [239, 137]. To optimize the comparison, the template set is pruned by only considering the words that start with the two letters closest to the point where the user initiated the gesture. Then, a pairwise comparison of the corresponding points is conducted to determine the similarities between the template and the drawn gesture. Particularly, the algorithm compares the angular difference between the angle formed by each point of the template and the drawn gesture [211]. The average angular difference is then used to approximate the similarity between the two shapes. Given a gesture G and a gesture template T, both are re-sampled at n points. The angular difference $\Delta\theta$ is calculated as follows, where $G\theta_i$ and $T\theta_i$ are angles formed at i^{th} point of the drawn gesture and the template, respectively.

Table 5.2: The actions required for word- and character-level text entry with Shapeshifter. OOV refers to out-of-vocabulary words.

Goal	**Action**	**Task**	**Cursor**
	Touch any surface (10-100 g)	*Display the cursor in inactive mode*	Grey
Enter	Apply & release force (100-400 g)	*Switch to the active mode*	Red
a	Move finger	*Position the cursor over the 1st letter of word*	Red
word	Apply and maintain extra force (>400 g)	*Perform the gesture*	Green
	Release extra force	*Complete gesture and enter the word*	Red/Grey
OOV	Apply & release extra force on a key	Enter the corresponding letter	Green
Pick	Apply & release extra force on a suggestion	Enter the suggested word	Green
Edit	Apply & release extra force on Backspace	Delete the last word or character	Green

$$\Delta\theta = \sum_{i=1}^{n} (G\theta_i - T\theta_i) \tag{5.1}$$

To estimate the difference in location between the two gestures, the distance between each corresponding point is computed. The sum of these individual point differences gives the total distance D between the shapes, where G_i and T_i are the vectors of points i of the drawn gesture and the template, respectively. The template yielding the highest similarity and the lowest distance between the shapes is picked as the best match and the respective word is selected as the most probable word.

$$D = \sum_{i=1}^{n} (G_i - T_i) \tag{5.2}$$

5.4 Long-Term Pilot Study: Text Composition

We conducted a pilot study to evaluate the performance of the proposed technique on composition tasks (i.e., free-from text entry). We were unable to conduct a full-length study since in-person studies are still prohibited in our institution due to the COVID-19 pandemic. The protocol described here was reviewed and approved by the IRB.

5.4.1 Participants and Apparatus

Two participants, aged 31 and 39 years, volunteered in the pilot study. They were both male and right-handed. None of them wore corrective eyeglasses. They both had some experience with VR (i.e., had used it at least once in the past) but not with the digital thimble. They were aware of gesture typing (i.e., had seen it before) but never used it to enter text on mobile devices.

The study used an Asus ROG GU501GM laptop with 16 gig RAM and Intel Core i7 processor and a Samsung Odyssey mixed reality HMD. The virtual environment displayed only the virtual keyboard and a text input area (Fig. 5.4).

5.4.2 Design and Procedure

The study was conducted remotely. We personally delivered the apparatus to each participant and scheduled individual video meetings with them. All forms (including the informed consent form) were completed and signed electronically. Upon completion of the study, we picked up the devices. All devices were disinfected before delivery and after pickup. During the video call, we demonstrated the system to the participants, asked them to practice with it under our guidance, and explained the study procedure. We encouraged them to ask us any questions they might have about the system or the study procedure. We then concluded the call.

Figure 5.5: A user composing text on the thigh in a seated position.

In the study, participants used Shapeshifter at home for one week (7 days) to compose free-form text on any desired topic. They composed text three times a day: in the morning, afternoon, and evening in three different settings: on a desk in a seated position, on the lap in a seated position, and on the palm or the back of the hand while standing up (Fig. 5.5). They could use the settings in any order. In each text entry episode, they were instructed to compose text for about 15 minutes on any desired topic (e.g., plans for the day, summary of the day, vacation plans, views about life, etc.). The system automatically recorded all interactions with the system and the entry speed of each episode using the commonly used words per minute (wpm) performance metric [4]. Upon completion of the study, participants were asked to review the composted passages to identify recognition errors, which we used to calculate the error rate (ER) metric [4]. We also conducted a debrief session to learn about their experience with Shapeshifter.

5.5 Simulation Study: Text Transcription

We conducted a simulation to estimate how fast novice users can transcribe text with Shapeshifter. After considering several existing models [177, 28, 25], we decided to use the curves, lines, and

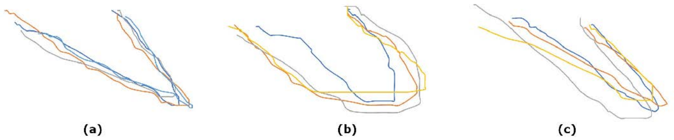


Figure 5.6: Gestures drawn for the most frequent word in the English language "the" by the participants on: a) the thigh, b) the desk, and c) the palm. Notice that the gestures drawn on the thigh and palm have much sharper corners.

Table 5.3: Results of the pilot study. Here, Length represents the average number of words in composted paragraphs.

Position	Surface	Length	WPM (Min-Max)	WPM (Mean)	ER (Min-Max)	ER (Mean%)
Seated	Desk	58-156	6.3-16.5	11.3 (SD = 2.7)	0.0-6.9	2.0 (SD = 2.1)
Seated	Lap/palm	59-130	5.5-11.6	8.9 (SD = 1.9)	0.4-6.9	2.6 (SD = 1.8)
Standing	Palm/ hand back	62-115	5.5-10.0	8.1 (SD = 1.2)	1.1-6.7	4.6 (SD = 2.2)

corners model [28] since it does not overestimate the gesture production time as much as the other models [195, 25]. The model describes gestures as compositions of curves, lines, and corners, but we considered only lines and corners since the effects of direction and corners are negligible in gesture production time [195]. The model describes lines and corners with a power function and a non-linear function, respectively. The production time (T) for a word with N letters is measured as:

$$T = \sum_{i=1}^{N-1} mL_i^n \tag{5.3}$$

Where L is the length of the i-th line and m and n are parameters of the model. To find these parameter values, we conducted a study (N = 5, M = 31 years), where novice participants (who did not use Shapeshifter before the study) drew straight lines of lengths 10, 20, 30, 40, and 60 mm at 0, 45, and 90° angles on the virtual keyboard, five times per combination, resulting in $5 \times 5 \times 3 \times 5 = 1,325$ data points. The gestures were drawn on a desk. A regression analysis on the data provided $m = 78.9$ and $n = 0.62$, with a 0.98 coefficient of determination. We then simulated the average transcription time of all 500 phrases in the MacKenzie & Soukoreff set [134] with 0, 1, 3, 5, and 10% error rates. For this, we estimated and added error correction time appropriate for the error rates as users tend to correct almost all errors in transcription tasks [5]. Error correction time for one incorrect word was estimated using the following equation:

$$T = T_p + T_d + T_r \tag{5.4}$$

Where, T_p is the preparation time (1,200 ms [107]), T_d is the deletion time (one Backspace), and T_r is the time to re-draw the gesture. The average cost of error correction was estimated at 2,977 ms per incorrect word. Table 5.4 presents the results of the simulation.

Table 5.4: Predicted text entry speed with Shapeshifter in transcription typing tasks.

ER	0%	1%	3%	5%	10%
WPM	27.3	26.2	24.1	21.9	16.4

5.6 Results and Discussion

Table 5.3 presents the results of the pilot study. Shapeshifter yielded on average 11 wpm on flat surfaces (e.g., a desk) and 9 wpm on the lap when sitting down, and 8 wpm on the palm and back of the hand when standing up in text composition tasks. Shapeshifter yielded a relatively lower entry speed reported for some gesture typing methods in the literature. We anticipated this since these techniques were evaluated in transcription typing tasks, where participants had to copy a sequence of presented text. In our study, participants composed text. Unlike transcription typing, people use a variety of cognitive processes when composing text, such as making plans, retrieving ideas from memory, making inferences, and creating and developing concepts [56, 225]. Regardless of this, Shapeshifter yielded comparable or higher entry speed than many gesture typing methods for VR (Table 5.1), which is inspiring. A simulation study predicted a 27.3 wpm error-free text entry rate in transcription typing tasks for novice users, which is faster than the existing gesture typing techniques. However, the simulation assumed an ideal surface, 0% error rate, and no OOV words, thus, the actual entry speed could be slower than predicted. Then again, the model did not consider users selecting words from the suggestion bar or the effects of practice, which could essentially result in a much faster entry speed than predicted.

In the debrief session, both participants praised the digital thimble for being light and comfortable but complained that the pressure sensor freezes at times and the optical sensor does not work properly when the finger is tilted toward the side of the sensor when it hits the surface. These issues were reported for all surfaces. We believe these issues can be addressed by using a flexible sensor cap that can re-adjust its orientation when users change their finger orientation. Both participants found gesturing in a seated position the easiest and the most comfortable, regardless of whether using a desk or the lap. However, they found gesturing on the lap more immersive. One participant commented, *"when I was drawing on the lap directly on the skin I felt I was more in the virtual environment "*. This suggests removal of extra physical devices can improve immersion. Likewise, gesturing on the palm and the back-of-hand whilst standing up was more physically taxing and the least comfortable, especially when entering text for an extended period of time. One participant commented, *“I feel typing on the hand has more fatigue than all the other positions”*. However, between the palm and the back-of-hand, the palm was more comfortable since the posture used to draw on the back-of-hand fatigued the wrist and the arm.

Fig. 5.6 visualizes the gestures drawn for the word “the” by the participants on various surfaces. One can see that the gestures drawn on the palm and the thigh had much sharper corners compared to the gestures drawn on the desk. The shape comparison algorithm yielded relatively higher match scores for the gestures drawn on the palm (92.5%, SD = 1.8) and the thigh (93.6%, SD = 1.04) than the ones drawn on the table (88.2%, SD = 1.22). This is not surprising since the templates were generated as straight lines with sharp corners. Regardless of the difference in the scores, the algorithm was able to identify all gestures accurately when coupled with the location channel.

Relevantly, prior studies showed that users tend to avoid sharp corners to maximize smoothness and reduce the total amount of jerk [57, 171]. The fact that the gestures drawn on the desk had rounder corners supports this. The gestures drawn on the palm and the thigh had sharper corners, presumably, due to the roughness of the surfaces. Hence, the effectiveness of the algorithm could be further improved by collecting samples from different surfaces and developing a model that can predict and compensate for the surface where gestures are drawn.

Participants found entering out-of-vocabulary words relatively difficult since navigating the finger to each letter took more time. Navigating the cursor to the Backspace key was also time-consuming. Both participants found the visual feedback of the cursor helpful in identifying different levels of pressure.

5.7 Conclusion

We presented Shapeshifter, a text entry technique for gesture typing using a digital thimble in VR. The digital thimble consists of an optical sensor to track the finger and a pressure sensor to detect touch and contact force. In a week-long in-the-wild pilot study, Shapeshifter yielded on average 11 wpm on flat surfaces and 9 wpm on the lap when sitting down, and 8 wpm on the palm and back of the hand when standing up with novice users in text composition tasks. A simulation study predicted a 27.3 wpm error-free text entry rate for novice users in transcription typing tasks on a desk. A post-pilot debrief session revealed that uneven surfaces made gesture typing with the thimble difficult and performing gestures when standing up caused more physical strain than when sitting down. This work demonstrated the potential of portable wearable devices for input in VR. In the next Chapter, we will refine the digital thimble to make it more robust for uneven surfaces. We will also explore the possibility of using it for other interactions within virtual environments.

Chapter 6

Digital Thimble for Free-hand Interaction

In the previous Chapter, we introduced a digital thimble designed for gesture typing in VR. Our empirical study revealed the potential of this wearable device to enhance user interaction within VR environments. Despite VR's growing penetration across diverse industries, from healthcare to education and entertainment, achieving precise and comfortable input and interaction remains a challenge. The digital thimble presents a promising solution to these issues, suggesting a new direction to improve user experience in virtual settings.

Current VR input methods predominantly involve handheld controllers provided with HMDs and bare-hand interaction facilitated by optical sensors [24, 68]. These techniques are centered around spatial gestures that, while expressive and engaging, can lead to physical strain and lack accuracy in certain contexts [68]. Spatial gestures also prove cumbersome in confined spaces, such as when seated in transportation, thus limiting VR's usability in various scenarios. Additionally, the optical sensors responsible for hand tracking are typically mounted on the HMDs and have a limited field of view (FOV). This limitation often forces users to maintain their gaze on their hands for interaction, which feels unnatural and restricts their posture. Optical tracking's effectiveness is further compromised in poor lighting conditions due to its inherent limitations in accuracy [180]. Although there are wearable solutions such as gloves, they tend to be bulky and impractical for extended use [47].

These challenges have prompted efforts to integrate traditional input devices, such as the mouse and keyboard, into VR interactions [68, 71, 70]. These devices can function within VR settings either independently, in a multimodal fashion, or for specific tasks. Despite being traditionally associated with 2D environments, these input methods have proven effective in 3D spaces, such as gaming or computer-aided design (CAD) [246]. They can be adapted for 3D interactions and, in certain tasks like object manipulation, may even surpass the performance of dedicated 3D input devices [162, 13]. However, locating and using these external devices while wearing an HMD can be cumbersome and distract users from their task. Moreover, switching seamlessly between interaction modes (e.g., from free-hand to mouse) without disrupting the virtual experience or immersion remains a significant challenge.

Therefore, a promising approach to overcoming these challenges is the adoption of wearable devices, particularly those designed for finger use. In the previous Chapter, we have shown that effectively tracking a single finger in VR can significantly enhance text input capabilities within VR environments. Despite the potential benefits of finger wearable devices for VR interactions, their application remains underexplored [136]. Moreover, there's a notable scarcity of empirical data regarding user performance with these devices across a variety of VR tasks, underscoring the need for further investigation into their utility and effectiveness.

In this Chapter, we redesign and assess the digital thimble for input and interaction within VR environments. Our goal is to provide an always-available, portable, and precise method that users can employ conveniently and comfortably in various postures and environments. Additionally, we investigate two selection methods: one that activates upon pressing or applying extra force, and another that triggers upon releasing the press or extra force, aiming to accommodate diverse user preferences and interaction styles.

The remainder of this Chapter is structured as follows. First, we review related work. Next, we describe the redesign of the digital thimble. We then outline our evaluation protocol, followed by a presentation of the results from two user studies. Finally, we discuss these results and conclude with directions for future work.

6.1 Related Work

This section discusses novel input devices, along with selection, teleportation, and sorting methods designed for VR. For a more comprehensive discussion on input and interaction in VR, refer to recent survey papers [201, 113]. Additionally, this section addresses hand and finger-tracking approaches in VR.

6.1.1 Input Devices for Virtual Reality

Handheld controllers are the most dominant input devices in VR. Most VR headsets come with handheld controllers, which are typically composed of buttons, triggers, thumb-sticks, and usually have motion-tracking capabilities. These features enable users to manipulate virtual objects or navigate through virtual spaces. The most common motion-tracking approach is ray-casting, which allows users to control a ray pointing to a target with hand movements and use the buttons or triggers to select and manipulate virtual objects [50]. Apart from ray-casting, various approaches that enable the use of the controller as a virtual mouse in the virtual world are also commonly used [112]. Despite their widespread usage, several issues with controllers have been identified by the research community [68, 246, 113]. First, controllers require users to hold them at all times, limiting the use of hands for performing other tasks. Second, since they necessitate performing mid-air gestures, they tend to be error-prone, lack precision, and cause fatigue during extended use. Furthermore, controllers are difficult to use in confined spaces, such as while seated on an airplane.

Researchers have proposed various input solutions to address these challenges, including the use of smartphones [114, 244], digital pens [167, 95, 178], tangible objects [14, 145], and even traditional mice [68, 246, 175]. However, most of these solutions are aimed at and optimized for specific contexts or use cases. For example, smartphones are predominantly used to provide text entry solutions in VR, while digital pens are primarily utilized to offer solutions for precise target selection. Consequently, these solutions outperform controllers in those specific scenarios.

In recent years, there has been a growing interest in using traditional mice in VR. This interest is attributed to their longstanding use in computer systems, their higher accuracy and precision in target selection, and user comfort, as users can rest their hand on a flat surface [175, 167, 13]. In studies investigating the accuracy and precision of mice according to Fitts' law, mice have consistently outperformed modern controllers in terms of throughput by around 12% [167, 175]. Recent work has shown that the mouse is also effective in a 3D world despite being a 2D input device [246]. However, mice require the use of the whole hand, thus limiting the hand's availability for other tasks. Besides, when released, users have to relocate the mouse on the desk, which is not always an easy task since users' sight is blocked by the headset.

There have also been hands-free input and interaction techniques developed to free up the hands. Nowadays, bare-hand interaction using mid-air gestures has become commonly used, thanks to the availability of affordable hand tracking technologies [126, 85]. However, the performance of these methods is reliant on the quality of the cameras and can suffer due to occlusion or other environmental factors. Mid-air gestures are also known to compromise comfort when used for prolonged periods. Other methods, such as head gestures and eye tracking, require an external input method to trigger them [245, 194]. Furthermore, they suffer from low precision and present a high physical strain. Some researchers have proposed the use of existing and novel wearable devices to mitigate these challenges, including smartwatches digital gloves, and finger wearables.

6.1.2 Wearable Devices

Wearable devices are devices that are designed to be used whilst worn directly on the body. They can be placed on different parts of the body including the eyes, ears, hands, fingers, feet, or even cover the entire body. The rise in wearables is powered by the advancements in embedded sensor technology, microcontrollers, and materials. This lets us integrate more sensors into even smaller wearables [108, 187]. In VR, wearables like rings [75], gloves [241, 222], finger worn devices [98, 97, 233] have been explored for input and interaction. Wearable devices have an advantage over handheld controllers since they are always on the user, thus eliminating the discoverability challenge. However, some VR wearables can be bulky or have steep learning curves [75]. The ideal solution would be lightweight, intuitive, and effective. We will categorize and review the latest advancements in wearable devices for VR input and interaction.

6.1.2.1 Hand and Finger Wearables

Researchers have explored various hand and finger wearables for VR interactions. These range from digital gloves for tracking and input [20, 192]to smaller finger-worn devices for specific touch interactions [98, 97, 233]. Bowman et al. [20] pioneered pinch gloves for VR text input, and some gloves incorporate IMUs for detailed hand and finger tracking [241, 222]. While gloves offer comprehensive tracking, they vary in sophistication. Basic gloves focus on hand position and gestures for standard VR interactions. More advanced gloves provide tactile and force feedback, allowing users to 'feel' virtual objects. However, these advanced gloves often use bulky sensors, limiting practicality and increasing cost (e.g., Meta's $15000 prototype [190]). Wearable mice (e.g., Fig. 6.2a), which represent a niche market on online shopping platforms, could serve as a bridge between traditional input methods and wearable technology, combining the accuracy and precision of a traditional mouse with the flexibility and portability of a wearable device. Nevertheless, the performance of wearable mice in VR has yet to be thoroughly investigated.

6.1.2.2 Wrist Wearables

Wrist-worn devices, such as smartwatches and wristbands, offer further possibilities for VR interaction. Though primarily used for notifications and fitness tracking, they have the potential for menu navigation and haptic alerts in virtual worlds. Techniques like TickTockRay [105] demonstrate smartwatch-based 3D pointing in VR, and WatchVR [84] explores broader smartwatch VR interactions. However, the small screen size of smartwatches poses a challenge. Other wrist-worn devices use electromyography (EMG) sensors to detect subtle muscle movements on the wrist and forearm [206, 33]. These sensors translate those movements into various commands in VR. While promising, these devices remain error-prone, sometimes requiring adaptation to ensure reliable interactions.

6.1.2.3 Foot Wearables

Foot-worn devices offer a unique approach to enriching VR experiences, particularly for locomotion and full-body immersion. Researchers have integrated various technologies into footwear, including pressure sensors in the sole and motion sensors worn on the ankle. Pressure-sensitive soles create an intuitive interface for virtual walking and interaction, as demonstrated by Matthies et al. [139] with their gesture detection system. Further, Park and Kim [159] utilized ground reaction force (GRF) sensors for identifying dynamic movements like running and jumping. However, foot-worn devices face challenges. Accommodating diverse foot shapes and sizes can be difficult, setup complexity varies depending on the technology, and applications often need to be specifically designed for foot-based input. Additionally, delivering realistic haptic feedback to the feet remains a significant challenge.

6.1.2.4 Full Body Wearables

The most common full-body wearables in VR are motion capture suits [102, 125, 30]. They utilize a combination of sensors (inertial, optical, etc.) embedded within a tight-fitting suit to precisely track body movement and translate it into the virtual environment. Motion capture suits offer high accuracy and low latency, making them ideal for applications like training simulations, virtual performance capture, and realistic avatar embodiment. Other full-body worn devices incorporate force-feedback mechanisms, actuators, and potentially electrical muscle stimulation to recreate sensations of touch, resistance, and impact within the virtual world. These exosuits are primarily used in areas like specialized training, rehabilitation, and high-end immersive experiences. Although full-body worn devices tend to produce realistic embodiment, they can be extremely expensive and often require specialized setup and calibration [125]. Some full-body solutions can be bulky or heavy, hindering natural movement and comfort during prolonged VR sessions. This makes tracking only hands and fingers a more practical and user-friendly approach

6.1.3 Hand and Finger Tracking in Virtual Reality

Most VR systems utilize a camera-based approach to track hand and finger movements, with the cameras mounted either on the headset or placed within the environment [126, 24]. However, they face challenges from environmental factors such as lighting, skin tone, and occlusion [126, 24]. For instance, it can be difficult for these systems to function in dark places, some marker-based methods struggle with different skin tones, and reflective materials might interfere with the sensing capabilities of some cameras. Consequently, research is actively exploring alternative sensors, including inertial measurement units (IMUs), optical sensors, and electromyography (EMG) in digital gloves [20, 192], wrist-worn devices [206, 33], and finger-worn devices [47], to overcome these limitations. These approaches demonstrate potential in certain scenarios, yet they encounter similar challenges related to comfort, scalability, and cost as outlined in Section 6.1.2.1.

6.1.4 Target Selection in Virtual Reality

Target selection in VR is accomplished through either direct manipulation, where virtual objects are selected using a virtual representation of the user's actual hands, or remote pointing, which involves controlling a virtual cursor using raycasting or a similar technique [175, 246, 126]. Direct manipulation enables users to reach out, grasp, and manipulate virtual objects, providing a sense of depth perception, typically facilitated by various optical hand-tracking systems. Although intuitive, this method can lead to high fatigue. Conversely, cursor movement techniques utilize controllers with six degrees of freedom (DOF), eye gaze, head movements, joysticks, digital pens, and various controllers [167, 175, 89], requiring users to point at an object and then perform an additional action to select it (a "switch"), such as pressing a button or issuing speech commands.

Raycasting is the most favored approach for target selection in VR, offering a selection method comparable to that on traditional desktop platforms. It functions similarly to a laser pointer, with users directing a ray of light at a target and confirming their selection with a trigger. Extensive research has been conducted to develop novel methods for optimizing raycasting in VR, aiming to enhance its efficiency and user experience [175, 246, 130, 168].

6.1.5 Teleportation in Virtual Reality

Locomotion is a crucial aspect of VR, enabling users to explore the virtual world. Researchers have investigated various locomotion techniques for virtual environments. Some techniques simulate walking by allowing users to walk in place while navigating the virtual environment, achieved through the use of treadmills [94], low friction surfaces [90], or unconventional devices like spheres [142]. One issue with this approach is that when users physically move, their eyes and inner ear are not always in sync, which can lead to symptoms such as nausea and dizziness [169]. Such approaches can also cause motion sickness. Additionally, these methods require heavy and expensive setups, which are not always practical or scalable. As a result, teleportation has become the dominant method for navigating the virtual environment. It is a virtual locomotion technique that allows users to move around a virtual environment without physically moving their body [169]. This is achieved by instantly transporting the user's avatar or point-of-view (POV) to a new location. Since teleportation does not involve any physical movement, it is less likely to cause motion sickness compared to other locomotion techniques [169]. Point-and-click is the most commonly used method for teleportation, allowing users to point to their desired destination and then click a button on the controller to teleport [169, 22]. However, researchers have explored alternative approaches to teleportation in VR, including teleportation by eye gaze [170], mid-air gestures [22], jump-gestures [17], and head movements [170].

6.1.6 Sorting in Virtual Reality

Sorting tasks are commonly utilized in VR to assess the performance of new input devices or techniques [238, 34]. These tasks require users to manipulate objects, such as cubes [34, 189, 188] or balls [247], by picking them up, holding them, and placing them in designated locations. Through such tasks, various aspects including tracking performance, and the device's comfort and usability, can be evaluated. Sorting tasks have been employed to examine collaborative tasks [77, 150], supply chain simulation [45], feedback approaches [189, 188], physical therapy [247], and even motivational relevance [122]. These evaluations provide deeper insights into user interactions within virtual worlds and inform the design of more effective VR systems. Consequently, we included sorting tasks in this work as a means to further evaluate the performance of the proposed input method.

6.2 Redesigning the Force-Based Digital Thimble

Based on the results and user feedback of Chapter 5, we redesigned the digital thimble for free-hand input and interaction in VR environments. This thimble is based on the premise that if we can accurately track the finger's movements, it can be effectively employed for a wide range of interactions.

Much like our earlier model, this thimble design emphasizes flexibility and comfort. It is intended to be worn on the index finger and seamlessly track the finger across nearly any diffuse opaque reflective surface. We have carefully maintained the sensor's position to the side of the finger, a placement that provides the best combination of tracking precision and user-friendliness. The thimble assembly process itself remains similar: the optical sensor is attached to the side of the index finger using a 3D-printed frame (Fig. 6.3c). However, we've extensively redesigned the 3D frame to optimize both user comfort and the stability of the sensor cap's surface contact.

Our frame redesign focused specifically on enhancing tracking performance on rough or uneven surfaces. Firstly, the sensor is now housed within a 3D-printed cap featuring a flat surface. This flatness guarantees reliable tracking even when the surface itself is irregular or uneven. The cap material was chosen for its firmness and smoothness, ensuring a consistent distance between the mouse sensor and the surface while minimizing friction. Secondly, we repositioned the section of the frame that holds the finger. It now sits on top of the finger, while the flexible supporting material extends underneath. In earlier design, the frame that holds the finger was underneath the finger, but testing revealed it impedes movement. Thus, this updated frame design gives the bottom of the finger more freedom for smoother interaction (Fig. 6.1). Through iteration, we made sure the frame cap is positioned in such a way that it does not interfere with the pressure sensor on the fingertip. Finally, we replaced the original cloth pressure sensor holder with lightweight, breathable finger cots [2]. This material is smoother, reduces friction, and significantly reduces or limits sweating compared to the previous material, enhancing the overall user experience for prolonged periods of use. Table 6.1 summarizes these key design changes.

To track finger movements with precision, our redesigned thimble integrates the same sensor as the previous one, the FCT 3065-XY optical mouse sensor (for technical details, see Section 5.2). Its 1200 dpi resolution ensures accurate tracking of finger gestures with precision and control. We repurposed this sensor and its associated circuit board from the Unique Station Mini Wireless Finger Mouse (Fig. 6.2a). To detect touch and contact force, we used the same force sensing resistor, the

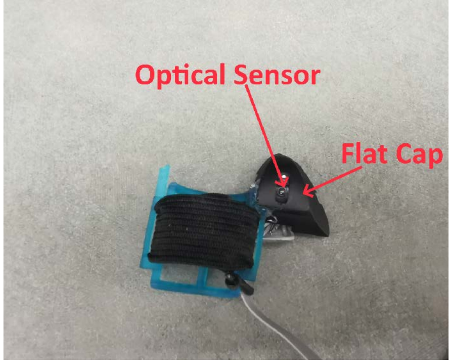


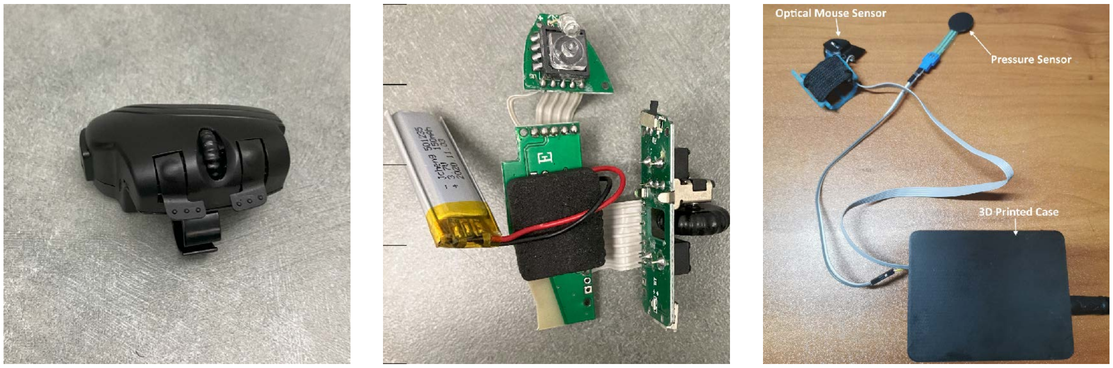
Figure 6.1: The redesigned thimble frame: Featuring a 3D-printed flat cap that houses the optical sensor. The black elastic band ensures a comfortable fit for various finger sizes. The 3D-printed blue finger holder now sits on top of the finger for improved usability.

Table 6.1: Thimble redesign features. The table compares the previous design features, the updated new design, and provides a rationale for each change.

Previous Design	New Design	Rationale
Mouse sensor without casing (cap)	Mouse sensor with casing	Ensures smooth interaction on surfaces and maintains a constant distance between the sensor and surface for improved tracking
Frame underneath finger	Frame above finger	Reduces disturbances when moving on surfaces
Soft material	Softer material	Reduces friction during interaction
Semi-breathable material	Breathable material	Improves comfort and reduces sweat
Cardboard case	3D printed case	Provides a more durable and precise casing

(FSR) 400 series pressure sensor [49] (for technical details of the FSR, see Section 5.2). The FSR is connected to an Arduino Uno Rev3 microcontroller. The microcontroller is housed in a custom-fit, 3D-printed wrist casing, offering improved durability over our previous cardboard-based case.

Our design considerations have placed a high priority on user comfort and wearability. To this end, we have selected lightweight components for the circuitry to ensure that the device is comfortable to wear on the wrist. Additionally, we have opted for a flexible material for the thimble, allowing it to accommodate a range of finger sizes. This choice enhances the overall versatility of the device, making it more adaptable to different users and potentially increasing its practicality for extended use. Importantly, by not depending on an HMD for finger tracking, our thimble maintains



(a) The finger mouse (b) Disassembled finger mouse (c) Components of the thimble

Figure 6.2: a) The Unique Station Mini Wireless finger mouse from which we collected the optical mouse sensor, b) the disassembled finger mouse, showing the circuit and the optical mouse sensor, c) the digital thimble components, showing the pressure sensor, the optical mouse sensor, and the 3D-printed case for the circuitry.

compatibility with various computer systems, expanding its potential for interaction beyond just VR environments.

6.2.1 Thimble Interaction

The digital thimble is designed for wear on the index finger and functions as a cursor control device. Users can simply glide their index finger across any surface, with the condition that the thimble's cap remains in contact with the surface. The optical sensor within the thimble detects the movements of the finger and transmits this data to the computer, which then adjusts the position of the cursor accordingly. This setup mirrors the functionality of a traditional mouse, with the notable convenience of having the mouse sensor directly attached to the index finger. The translation of finger movements into cursor movements is handled through the Unity3D mouse input API, allowing for a seamless integration of physical gestures into digital commands.

A unique feature of the digital thimble is its utilization of contact force for selection. Through rigorous lab trials, we determined an activation threshold of 400 g. This threshold was carefully chosen to balance the prevention of unintended selections with ensuring user comfort during index finger use. It is set at a level that is sufficiently high to avoid accidental activations, yet still low enough to provide a comfortable user experience. The thimble incorporates the following two methods for target selection, enhancing its adaptability to different user preferences and scenarios.

1. Cursor movement and **press**. In this method, users navigate the cursor to the intended target. To finalize the selection, they exert pressure exceeding the 400 g threshold.

2. Pressure-based movement and **release**. In this method, users keep pressure above the 400 g threshold to adjust the cursor's location. Upon deciding to select, they lessen the pressure, thereby confirming their selection.

6.2.2 Visual Feedback

To improve user understanding of the system's status, we incorporated various visual feedback cues. The cursor changes to a green color to signify its active moving state and turns black to indicate an inactive state, where it is not ready for movement. In the press method, the cursor turns green when the system senses the finger's presence on a surface, signaling readiness for movement. On the other hand, with the release method, the cursor usually stays black, turning green only when the system detects pressure being applied by the finger on a surface. The use of green for the cursor's active state is intentionally chosen due to its universal association with the "go" signal, aiding users in intuitively grasping the system's current operational mode [46].

6.3 Evaluation Protocol

We conducted a comprehensive evaluation of our digital thimble through two user studies. The first study utilizes Fitts' law principles to benchmark the thimble's performance against two commercial input devices: an Oculus Touch VR controller and an AOKID Creative finger mouse (Fig. 6.3). In this study, we also evaluate the effectiveness of both the press and release selection methods. The second study further explores the performance of these methods within two commonly encountered VR scenarios: teleportation and sorting. Together, these studies provide valuable insights into the functionality of the thimble, as well as a commercial finger mouse, within real-world VR applications, highlighting their respective advantages and areas for improvement.

(a) Oculus touch controller (b) AOKID Creative finger mouse (c) Digital thimble

Figure 6.3: The controller, finger mouse, and digital thimble utilized in the evaluations.

6.3.1 Oculus Touch Controller

The controller is designed to be held in the hand and is selected for its widespread use as the primary input device across various VR systems. These controllers combine embedded tracking with external sensors to accurately monitor the user's hand position and orientation within the virtual space. They feature buttons for interacting with virtual objects and, in some cases, are equipped with analog sticks to facilitate navigation within the virtual environment (Fig. 6.3a).

In our setup, we utilize mid-air gestures with the controller to manipulate the cursor, preferring this method over the traditional use of analog sticks due to the prevalence of mid-air gestures in VR controller usage [126]. To control the cursor, users simply move the controller through the air, with the controller's horizontal and vertical movements directly translating to the cursor's movements along the x and y axes, respectively.

This mapping is achieved using the Unity3D Oculus integration. Despite the controller being a 3D device, our implementation focuses solely on cursor control through movements in the x and y directions, simplifying the interaction mechanism while maintaining effective control.

6.3.2 AOKID Creative Finger Mouse

The AOKID Creative Finger Mouse has gained popularity within a niche market, especially in the Asian region. Worn over the index finger, it offers users the flexibility to multitask, such as typing on a keyboard, while still wearing the device. Operating similarly to a conventional mouse, it features left and right buttons that are accessible by the thumb and can be used on any opaque diffuse reflective surface. We included this device in our study because its form factor closely resembles that of our own design, making it a pertinent comparison point in our research. Besides, while the use of traditional mice in VR has been thoroughly investigated in the literature, the applicability and performance of wearable mice have not yet been evaluated. For our implementation, we mapped mouse movements using the Unity3D mouse input API, allowing us to directly compare its performance with our digital thimble in a VR context.

6.3.3 Experimental System

The experimental system was developed using Unity3D v2019.4.8f1, with the Oculus Unity Integration toolkit incorporated to facilitate support for Oculus controllers. This setup allowed for the control of the cursor through the three devices under investigation. Users could manipulate the cursor and select their desired targets using either the press or the release method with any of these devices, enabling a thorough evaluation of their performance and usability. For selection using the press method with the controller and the mouse, users move the cursor to the target and then confirm the selection by pressing the left button (for the mouse) or the trigger (for the controller). For the release method, users press and hold the left button (mouse) or the trigger (controller), navigate the cursor to the target, and then release the button or trigger to confirm the selection.

6.4 User Study 1: Fitts' Law

This study conducted a comparative analysis of target selection performance using the digital thimble, controller, and finger mouse, grounded in Fitts' law principles. It also aimed to evaluate the efficiency of both press and release selection methods.

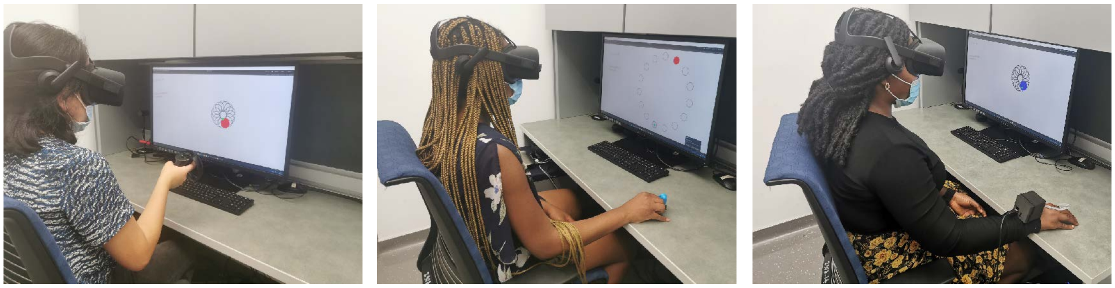
Fitts' law, as outlined in ISO 9241-9 and ISO 9241-411, is a standard method for assessing target selection efficiency on computing systems [133, 198]. For a detailed description of the Fitts' law protocol refer to Section 4.4.

6.4.1 Participants

Twelve participants took part in the user study (M = 27.5 years, SD = 4.7). Six of them identified as female, and six as male. All participants had attained a university-level education and self-reported as right-handed. Five participants had previous experience with VR systems. None required corrective eyeglasses. Each participant was compensated with U.S. $15 for their involvement.

6.4.2 Apparatus

The experimental setup was run on a Windows 10 HP OMEN desktop, powered by an AMD Ryzen 5 2500X Quad-Core processor, 8 GB of RAM, and an Nvidia GeForce GTX 1060 graphics card. The setup featured an Oculus Rift HMD with an OLED display offering a resolution of 2060 × 1200 ppi, a refresh rate of 90 Hz, and a 110° FOV. It was also connected to an HP Omen 32-inch gaming monitor with a 2560 × 1440 pixel resolution. The Fitts' law protocol was implemented using Unity3D v2019.4.8f1. The controller weighed 153 g, the finger mouse 25 g, and the digital thimble 124 g with its circuit box (5 g without).



(a) Controller (b) Finger mouse (c) Thimble

Figure 6.4: The setup used in the first user study. The pictures show three participants performing target selection tasks with the three examined input devices.

6.4.3 Design

The experiment was a 3 × 2 × 3 × 3 within-subjects design. The independent variables and levels were as follows.

- Device (*Mouse*, *Thimble*, *Controller*)
- Selection Method (*Press*, *Release*)
- Amplitude (30, 115, 200 pixels)
- Width (8, 16, 24 pixels)

There were fifteen trials per sequence, with selected amplitudes ranging between 30 and 200 pixels to accommodate the headset's FOV. Amplitudes above 200 pixels necessitated additional head movements for item visibility, while those below 30 pixels were deemed excessively small. Widths were chosen between 8 and 24 pixels, reflecting the minimum size comfortably visible through the HMD, with widths exceeding 24 pixels considered too large and impractical for the study's objectives.

The dependent variables in the study included throughput, movement time, target re-entries, and error rate. Target re-entries refer to the number of times the cursor re-entered a target in a trial after the initial entry, measured as a count per trial. The error rate, on the other hand, is the average percentage of trials in which selections were made outside the intended target boundaries, reflecting the accuracy of target selections.

6.4.4 Procedure

The study started with a researcher explaining the research goals and demonstrating the system to participants. After this introduction, participants gave their consent by signing an informed consent form and filling out a demographics questionnaire. For comfort and to ensure reliability, participants were seated at a desk in a posture conducive to using the thimble and mouse on the desk surface and the controller for mid-air gestures. Chair adjustments were made as needed for optimal comfort. Participants then underwent a 10-minute training session, which involved selecting ten circular targets, each 18 pixels in diameter, arranged within a 120-pixel diameter circle. This training covered the use of all three devices across both selection methods, resulting in six training conditions.

After the training session, participants moved on to the main study, selecting fifteen targets using the six available methods in a counterbalanced order. They were advised to balance speed and accuracy while staying comfortable. To avoid fatigue, a 2-minute break was scheduled after every three sequences, and a 3-minute break after completing each condition. Participants could request at most 3 extra breaks or extend the scheduled ones by 3 minutes as needed.

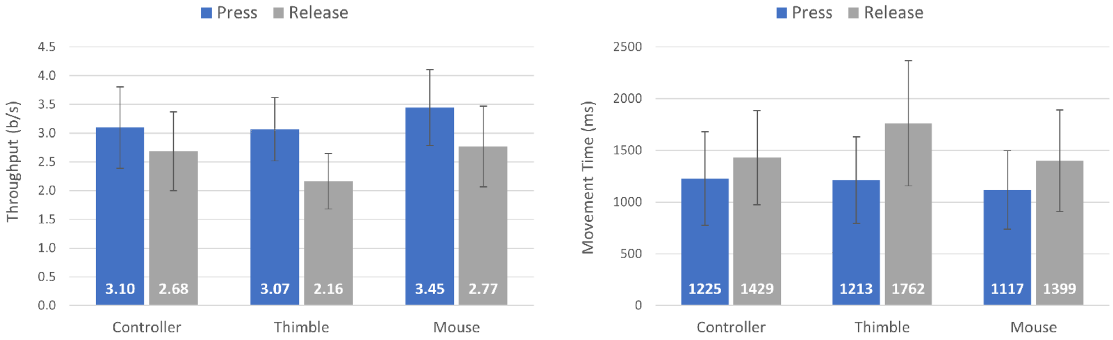
After finishing all conditions, participants completed the NASA-TLX questionnaire to assess the perceived workload of the methods used. They also filled out a custom questionnaire to rate their perceived performance and express their preferences for the selection methods. The study wrapped up with a short debriefing session, allowing participants to share comments and insights about their experimental experience and their questionnaire responses.

6.4.5 Results

The entire study, including the demonstration, questionnaires, and breaks, took approximately 50 minutes to complete. A Martinez-Iglewicz test confirmed the normal distribution of response variable residuals. Mauchly's test verified the equality of variances across populations, allowing for the use of a repeated-measures ANOVA in our analyses. For subjective data involving more than two levels, a Friedman test was employed. Furthermore, we report effect sizes for statistically significant findings: eta-squared (η^2) for ANOVA, Pearson's r for the Wilcoxon Signed-Rank test, and Kendall's W for the Friedman test.

6.4.5.1 Throughput

An ANOVA identified a significant effect of device on throughput ($F_{2,22} = 18.87, p < .0001, \eta^2 = 0.1$). The mouse achieved the highest mean throughput at 3.11 bps, followed by the controller at 2.89 bps, and the thimble at 2.61 bps. There was also a significant effect of selection method ($F_{1,11} = 73.16, p < .0001, \eta^2 = 0.2$). The press selection method demonstrated superior performance, yielding a mean throughput of 3.20 bps, whereas the release method resulted in a slightly lower mean throughput of 2.54 bps. A Tukey-Kramer test revealed that all input devices were significantly different from each other in terms of performance, but they all exhibited superior perfor-

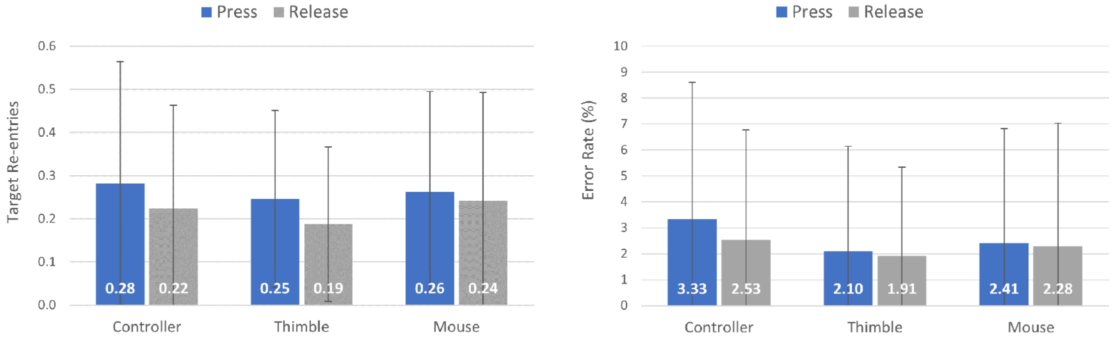


(a) Throughput (bps)

(b) Movement time (ms)

Figure 6.5: Average throughput and movement time categorized by input device and selection method. Error bars represent ±1 standard deviation.

mance when using the press selection method compared to the release selection method. Fig. 6.5a displays the average throughput data categorized by input device and selection method.



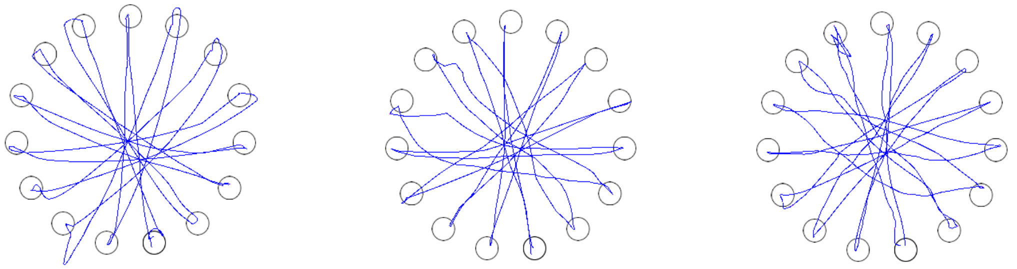
(a) Target re-entries (count/trial)

(b) Error rate (%)

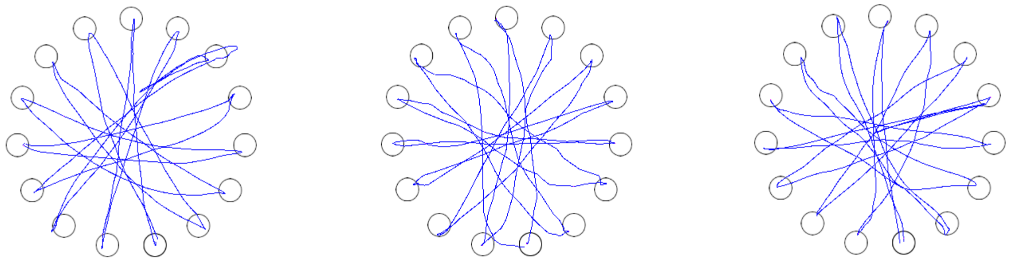
Figure 6.6: Average target re-entries and error rate categorized by input device and selection method. Error bars represent ±1 standard deviation.

6.4.5.2 Movement Time

An ANOVA identified a significant effect of device on movement time ($F_{2,22} = 17.31, p < .0001, \eta^2 = 0.03$). The mouse exhibited the quickest performance with a mean time of 1,258 ms, followed by the controller at 1,327 ms, and the thimble at 1,487 ms. There was also a significant effect of selection method ($F_{1,11} = 51.56, p < .0001, \eta^2 = 0.1$). The press selection method achieved the fastest performance with a mean time of 1,185 ms, while the release method resulted in a slightly longer mean time of 1,530 ms. A Tukey-Kramer test revealed the thimble required a significantly longer movement time compared to both the mouse and the controller. Additionally, the test showed that all input methods significantly outperformed when utilizing the press selection method in comparison to the release method. Fig. 6.5b illustrates the average movement time categorized by input device and selection method.



(a) Controller + Press (b) Thimble + Press (c) Finger Mouse + Press



(d) Controller + Release (e) Thimble + Release (f) Finger Mouse + Release

Figure 6.7: Cursor trace examples for the six study conditions.

6.4.5.3 Target Re-entries

An ANOVA failed to identify a significant effect of device on target re-entries ($F_{2,22} = 0.80, p = .5$). Results indicated that the input devices produced similar levels of target re-entries. Specifically, the thimble exhibited the lowest average count of target re-entries at 0.22 per trial, followed closely by the mouse and the controller, both at 0.25 per trial. However, there was a significant effect of selection method ($F_{1,11} = 9.05, p < .05, \eta^2 = .01$). The release selection method demonstrated the lowest average count at 0.22 per trial, while the press method yielded a slightly higher average count of 0.26 per trial. The results of a Tukey-Kramer test did not reveal any clear and consistent patterns regarding the pairing of specific input devices with different selection methods. Fig. 6.6a displays the average number of target re-entries, organized by input device and selection method. Fig. 6.7 provides examples of cursor traces for the six conditions examined in the study.

6.4.5.4 Error Rate

An ANOVA identified a significant effect of device on error rate ($F_{2,22} = 5.95, p < .05, \eta^2 = 0.01$). The thimble achieved the lowest error rate at 2.01%, followed by the mouse at 2.34%, and the controller at 2.39%. There was no significant effect of selection method ($F_{1,11} = 3.06, p = .10$). Both the press and release selection methods resulted in comparable error rates. Specifically, the press method had an error rate of 2.61%, while the release method exhibited a slightly lower error rate of 2.23%. A Tukey-Kramer test revealed that the thimble was significantly more accurate than the controller. Fig. 6.6b presents the average error rate categorized by input device and selection method.

6.4.6 Subjective Feedback

After completing the experimental tasks, participants provided feedback via two questionnaires. The first, the raw NASA-TLX, allowed them to evaluate the perceived workload of each selection method on a 20-point scale. We employed a non-parametric Friedman test to analyze this data, presenting raw TLX scores by examining the sub-scales individually, which is a common adaptation of the NASA-TLX [78]. Following this, participants filled out a custom questionnaire using a 5-point Likert scale to rate perceived usability aspects such as speed, accuracy, user-friendliness, naturalness, and their overall preference.

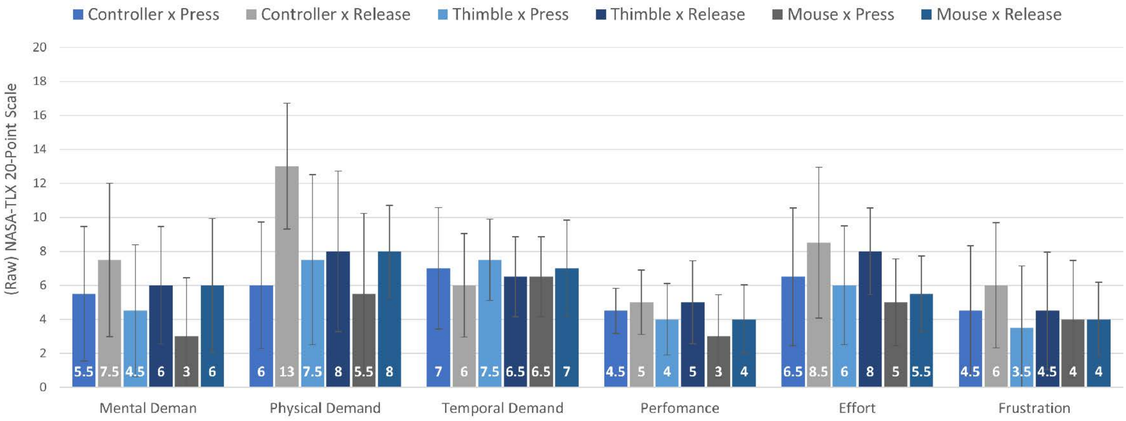


Figure 6.8: The median perceived workload across user study conditions as measured by a 20-point NASA-TLX questionnaire, where a scale from “1” to “20” indicates a range from “very low” to “very high” for all factors except performance, where “1” to “20” represents a spectrum from “perfect” to “failure”. Error bars represent ±1 standard deviation.

6.4.6.1 Perceived Workload

A Friedman test identified a significant effect of condition (device × selection method) on mental demand ($\chi^2 = 11.37, df = 5, p < .05, W = 0.2$), physical demand ($\chi^2 = 21.39, df = 5, p < .001, W = 0.4$), performance ($\chi^2 = 13.00, df = 5, p < .05, W = 0.2$), and frustration ($\chi^2 = 13.12, df = 5, p < .05, W = 0.2$). However, there was no significant effect on effort ($\chi^2 = 10.87, df = 5, p = .05$) or temporal demand ($\chi^2 = 10.87, df = 5, p < .8$). Fig. 6.8 illustrates the median perceived workload ratings for all conditions in the user study.

6.4.6.2 Perceived Usability

A Friedman test identified a significant effect of condition (device × selection method) on perceived speed ($\chi^2 = 21.66, df = 5, p < .001, W = 0.4$), accuracy ($\chi^2 = 11.60, df = 5, p < .05, W = 0.2$), user-friendliness ($\chi^2 = 21.07, df = 5, p < .001, W = 0.4$), naturalness ($\chi^2 = 24.53, df = 5, p < .001.W = 0.4$), and preference ($\chi^2 = 26.22, df = 5, p < .001, W = 0.4$). Fig. 6.9 illustrates the median perceived performance ratings for all conditions in the user study.

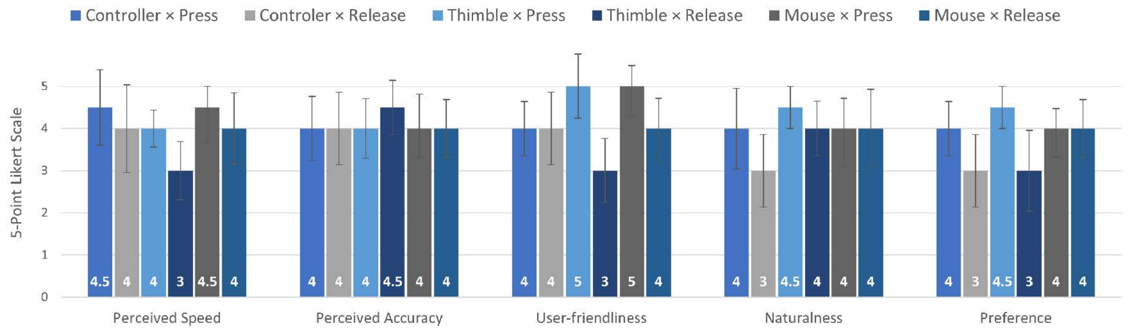


Figure 6.9: The median perceived usability of the user study conditions, rated on a 5-point Likert scale ranging from "1" (strongly disagree) to "5" (strongly agree). Error bars represent ±1 standard deviation.

6.4.7 Discussion

The finger mouse exhibited superior throughput and quicker movement times compared to both the controller and the thimble. Moreover, the press selection method consistently surpassed the release method in throughput and movement times across all devices. This disparity may arise from the extended selection times caused by executing an action while simultaneously moving.

The impact of the release method was notably more significant on the thimble, potentially due to the friction encountered between the thimble and the surface when pressure was applied during movement. The results also showed that while the controller generally outperformed the thimble, the difference between them was not significant when using the press method. This suggests that the thimble when employing the press method, could match the controller's effectiveness. As expected, mirroring the traditional mouse's performance, the finger mouse excelled over the controller in VR target selection tasks.

The thimble demonstrated superior accuracy and precision over the controller and mouse. Additionally, the release selection method led to fewer target re-entries than the press method, enhancing users' precision. These advantages could be attributed to the thimble's form factor and portability, enabling seamless integration with the user's finger without requiring additional fingers for operation, unlike the wearable mouse. The benefits could also arise from the speed-accuracy trade-off effect, that is, users made fewer errors and achieved greater precision due to the slower nature of the method.

6.4.7.1 Subjective Feedback

Participants found the thimble to be the most comfortable device among the options. The controller, on the other hand, was associated with significantly higher physical discomfort. This was linked to the need to perform mid-air gestures, which are known to induce physical strain as found in Chapter 4. Participants described their experience with the controller as *"physically demanding"*, *"stressful"*, and *"uncomfortable"*. Interestingly, while the mouse was considered more efficient, participants also found it uncomfortable to use for extended periods. Some participants mentioned discomfort related to using the thumb for clicking, while others found it novel and appreciated its unique characteristics. The higher comfort rating for the thimble could be attributed to its compact and easily adaptable design, allowing for comfortable postures when worn. Furthermore, when paired with the press method, participants found it to be more natural and familiar, akin to operating a smartphone. However it is worth noting that one participant expressed discomfort with wearing something on the wrist. Thus, future iterations of the thimble prototype could benefit from a self-contained design to address potential discomfort related to wrist-worn accessories.

Despite the thimble exhibiting slightly slower performance than the other devices, participants rated it similarly in terms of speed and accuracy. Notably, when it came to preference for continued use in VR, participants rated the thimble higher than the other devices, indicating a preference for its convenience and user experience. However, participants did express concerns regarding the challenge of knowing when the right amount of pressure was applied while using the thimble, potentially affecting its usability. To address this issue, participants suggested the implementation of additional forms of haptic feedback to provide users with more guidance. This feedback could have a positive impact on the thimble's release method, potentially improving its performance and usability.

The results underscore the potential of finger wearable devices in VR. The wearables outperformed the controller, a conventional input device in VR settings. Additionally, participants reported higher levels of comfort and usability when using wearable devices compared to the controller. These findings emphasize the importance of developing portable devices. In this study, the thimble and mouse exemplified portability by being worn on the finger or held in one hand. The thimble's design, allowing for single-finger usage and compatibility with various surfaces, makes it particularly valuable in confined spaces and scenarios that require enhanced mobility. Moreover, the thimble's "always-on" nature means users do not have to remove it when switching to other interaction methods, such as hand gestures, ensuring seamless and uninterrupted user experiences. These insights highlight the potential for the thimble to offer versatile and user-friendly input solutions in VR environments.

6.5 User Study 2: Teleportation & Sorting

We carried out a second user study to assess and compare the performance of the proposed digital thimble, finger mouse, and controller within VR environments, focusing on teleportation and object sorting scenarios. The study utilized the same setup as the preceding study, with the experimental system developed using Unity3D v2019.4.8f1.

6.5.1 Participants

Twelve participants took part in the study (*M* = 31.8 years, *SD* = 5.7). Six identified as female and six as male. All participants had attained a university-level education and self-identified as right-handed. Approximately half of the participants (five out of twelve) had prior experience with VR. None of them had participated in the previous study. All participants were compensated with U.S. $15 for their participation in the study.

6.5.2 Design

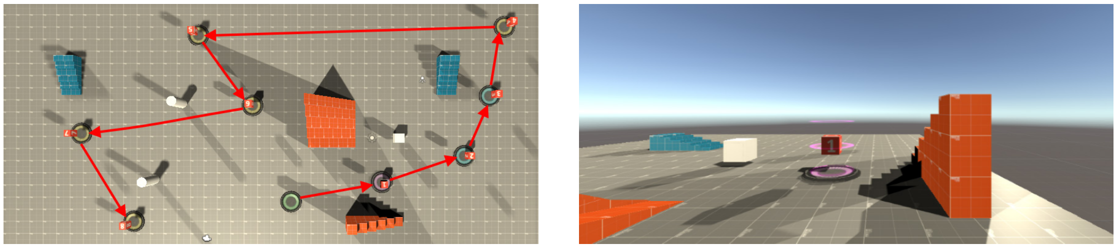
The study employed a within-subject design comprising two sessions: teleportation and sorting, with counterbalanced session orders. The independent variable was the input device, with three levels: finger mouse, thimble, and controller. In the teleportation session, participants teleported to eight predetermined targets, while the sorting session involved sorting ten sequences. Device order was also counterbalanced to minimize order effects. The dependent variables were the following performance metrics:

- **Task completion time** (in milliseconds) represents the average time taken by participants to complete a task. For teleportation, it denotes the average time needed to teleport to all destinations, while for sorting, it signifies the average time taken to correctly arrange all cubes.
- **Accuracy** (in percentage) indicates the average percentage of tasks accurately performed by the users. For teleportation, an error is recorded when participants select a location outside the current teleport target. In the sorting task, errors occur when the completed sequence deviates from the correct order.

6.5.3 Teleportation Tasks

To implement teleportation, we adopted the "point and select" technique [22], where users point to their desired destination in the virtual environment and select it to initiate teleportation, using raycasting to point. The ray extended up to 2 m, allowing targeting at various distances, controlled in the x and y axes by thimble movement. Selection was made by pointing the ray at the location and applying pressure over 400 g. Unlike typical teleportation implementations where viewpoint changes with head movement, we kept users seated and allowed viewpoint adjustment via input devices, similar to first-person shooter games but with ray control and viewpoint rotation decoupled. To change the viewpoint, users applied and maintained pressure while moving the device. For the mouse and controller, ray movement and target selection were linked to their movement, with a similar technique for viewpoint rotation. The teleportation scene featured eight targets on a 25×50 meter plane (Fig. 6.10a), designed as cylindrical objects with dynamic animations for visibility (slowly moving up and down), using Unity Particle System, and labeled with numerical identifiers for clarity (Fig. 6.10b).

During the teleportation session, participants visited eight predetermined destinations, following a route with varying distances (6–32 m) and angles (10–130°). The first four targets allowed direct teleportation, while the last four required viewpoint rotation. Errors, marked by a beep sound, occurred if deviating from the correct target, with the sequence starting from a designated green



(a) Teleport destinations (b) Screenshot of teleport target

Figure 6.10: a) A bird's-eye view of the teleportation destinations. The red arrows indicate the designated path that participants are required to follow. The green target represents the initial starting point within the virtual environment. b) A screenshot of a teleportation target in a VR environment, featuring a blush pink cylindrical animation and a cube displaying the target's number.

target. Figure 6.11 depicts the setup involving three participants, each using one of the three devices (digital thimble, controller, and finger mouse) for teleportation tasks.

(a) Controller (b) Finger mouse (c) Digital thimble

Figure 6.11: Three participants using the controller, finger mouse, and digital thimble for teleportation, respectively.

6.5.4 Sorting Tasks

In the sorting scenario, virtual cubes served as the objects for the task. We created an immersive scene with four numbered cubes placed on a table in front of the users (Fig. 6.12). Users selected cubes by directing a ray, controlled by moving the thimble on a surface, within a 2 m range in the virtual environment. When the ray contacted a cube, it changed color from red to semi-transparent light green, signaling successful targeting, similar to how a cursor changes outside VR. Selection required applying pressure above 400 g, allowing the cube to be picked up, moved, and placed by pressing the thimble again. Cube movement was limited to the x and y-axes, with gravity ensuring cubes fell onto the table if not placed directly on it. Selection and manipulation with the controller and mouse mirrored this process, with the ray's direction controlled by their movements. Selection was done via a mouse button or controller trigger. This process entailed pointing the ray at a cube, selecting it, moving it by manipulating the ray, and confirming the placement by re-selecting. To ensure users remained focused and undistracted, the scene was deliberately designed to be simple, including just a table, numbered cubes, and a control button to start and end the task. Additionally, we used color schemes that offered clear visual contrast, making it easier for users to distinguish between different objects.

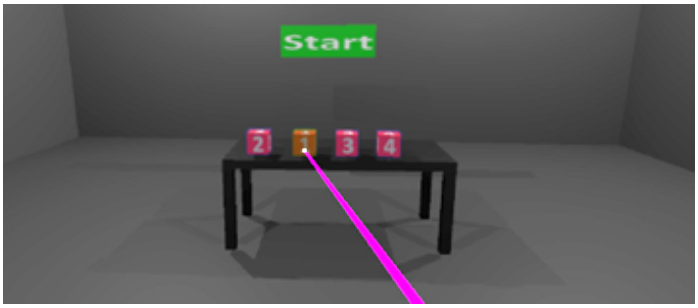


Figure 6.12: A sorting scene featuring four numbered cubes on a table, a light purple selection ray, a highlighted selected cube in light green, and a button at the back labeled “Start” (which changes to “Finish” when activated).

During the sorting session, participants were tasked with arranging four numbered cubes in ascending order from 1 to 4. We designed 10 distinct sequences based on the Levenshtein Distance (LD) criteria [124], including 3 sequences with an LD of 2, 4 sequences with an LD of 3 (medium difficulty), and 3 sequences with an LD of 4. To begin sorting, participants clicked a start button using the ray, and to move on to the next sequence, they clicked a finish button (Fig. 6.12). The system did not provide feedback on the arrangement or errors, and participants were told that only the order of the cubes mattered, not their distances apart. Fig. 6.13 illustrates participants engaging in the sorting task using the three devices under examination.

(a) Controller (b) Finger mouse (c) Digital thimble

Figure 6.13: Three participants using the controller, finger mouse, and digital thimble for sorting cubes, respectively.

6.5.5 Procedure

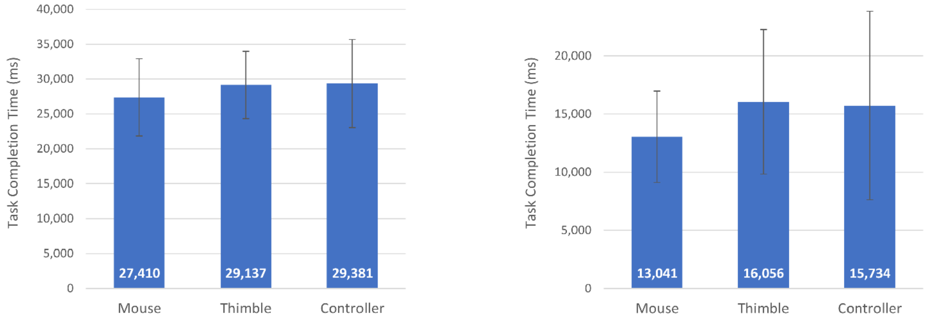
The study began with a researcher outlining the objectives and demonstrating the sorting and teleportation scenarios to the participants. After providing informed consent and completing a demographics questionnaire, participants positioned themselves comfortably at a desk with a VR headset, similar to the setup in Study 1 (Fig. 6.4). They were encouraged to adjust the chair for optimal comfort. Participants then underwent two 5-minute training sessions to familiarize themselves with the sorting and teleportation scenes. In the sorting training, they arranged three different sequences of cubes numbered 1 to 4. The teleportation training involved teleporting to three destinations set at least 90 degrees apart. Device use was randomized during these sessions.

After the training, participants moved on to the main study, engaging in the sorting and teleportation scenarios in a counterbalanced order. They took a compulsory 2-minute break between changing devices and a 5-minute break after each scenario. Participants had the flexibility to extend these breaks by up to an additional 1 minute if needed.

Upon completing the scenarios, participants filled out two questionnaires to assess the perceived workload and device usability. The NASA-TLX questionnaire measured perceived workload, while a custom questionnaire on a 5-point Likert scale gauged device usage experience.

6.5.6 Results

The entire study, including demonstrations, questionnaires, and breaks, took approximately fifty minutes to complete. A Martinez-Iglewicz test confirmed that the residuals of the response variables were normally distributed. Mauchly's test showed equal variances across populations, allowing for the use of repeated-measures ANOVA in our analyses. For subjective data with more than two levels, we employed a Friedman test. Additionally, we report effect sizes for statistically significant findings, including eta-squared (η^2) for ANOVA, Pearson's r for the Wilcoxon Signed-Rank test, and Kendall's W for the Friedman test.

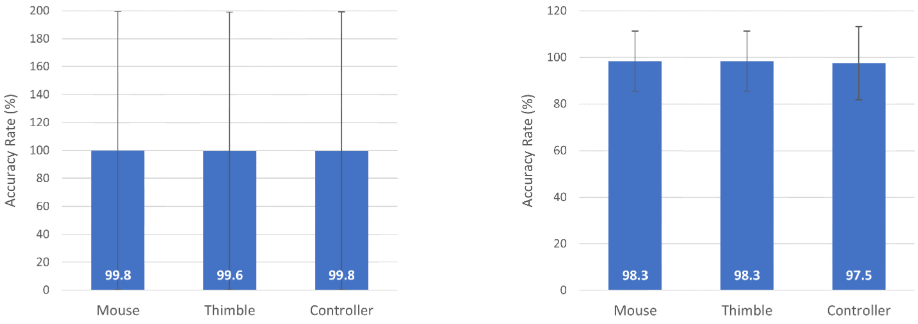


(a) Teleportation (b) Sorting

Figure 6.14: Average task completion time (milliseconds) categorized by input device. Error bars represent ±1 standard deviation.

6.5.6.1 Task Completion Time

An ANOVA failed to identify a significant effect of device on teleportation task completion time ($F_{2,22} = 1.10, p = .35$). On average, the mouse achieved the fastest completion time at 27,410 ms for teleportation, followed by the thimble at 29,137 ms, and lastly, the controller at 29,880 ms. But an ANOVA did identify a significant effect of device on sorting task completion time ($F_{2,22} = 3.61, p < .05, \eta^2 = 0.04$). The mouse achieved the fastest completion time in the sorting task at 13,040 ms, followed by the controller at 15,834 ms, and the thimble at 16,056 ms. A Duncan test indicated that the mouse was significantly faster than the other two devices in sorting tasks, while there was no significant difference between the controller and the thimble. Fig. 6.14 presents the average task completion time categorized by the three examined input devices.



(a) Teleportation (b) Sorting

Figure 6.15: Average accuracy rate (%) categorized by input device. Error bars represent ±1 standard deviation.

6.5.6.2 Accuracy

An ANOVA did not reveal a significant effect of device on teleportation accuracy ($F_{2,22} = .54, p = .60$). The mouse exhibited the highest accuracy, with a 99.8% success rate, followed closely by the controller at 99.7%, and the thimble at 99.6%. An ANOVA also failed to identify a significant effect of device on sorting the accuracy ($F_{2,22} = 0.19, p = .83$). All three devices exhibited excellent accuracy in the sorting task, with the mouse achieving a 98.3% accuracy rate, the thimble achieving 98.3%, and the controller achieving 97.5%. Fig. 6.15 presents average accuracy rate categorized by the three examined input devices.

6.5.7 Subjective Feedback

After completing the experimental tasks, participants provided feedback via two questionnaires. The first, the raw NASA-TLX, allowed them to evaluate the perceived workload of each selection method on a 20-point scale. We employed a non-parametric Friedman test to analyze this data, presenting raw TLX scores by examining the sub-scales individually, which is a common adaptation of the NASA-TLX [78]. Following this, participants filled out a custom questionnaire using a 5-

point Likert scale to rate perceived usability aspects such as speed, accuracy, user-friendliness, naturalness, and their overall preference.

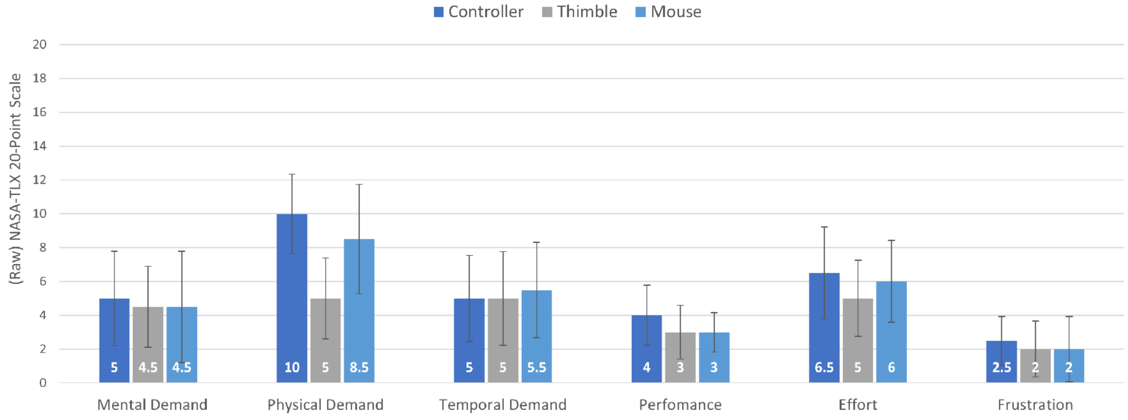


Figure 6.16: The median perceived workload across user study conditions as measured by a 20-point NASA-TLX questionnaire, where a scale from “1” to “20” indicates a range from “very low” to “very high” for all factors except performance, where “1” to “20” represents a spectrum from “perfect” to “failure”. Error bars represent ±1 standard deviation.

6.5.7.1 Perceived workload

A Friedman test identified a significant effect of device on physical demand ($\chi^2 = 6.89, df = 2, p < .05, W = 0.3$). However, no significant effect was identified on mental demand ($\chi^2 = .05, df = 2, p = .10$), temporal demand ($\chi^2 = 2.54, df = 2, p = .28$), performance ($\chi^2 = .74, df = 2, p = .70$), effort ($\chi^2 = .38, df = 2, p = .83$), or frustration ($\chi^2 = .07, df = 2, p = .97$). Fig. 6.16 illustrates the median perceived workload ratings for all conditions in the user study.

6.5.7.2 Perceived usability

A Friedman test failed to identify a significant effect of device on speed ($\chi^2 = 3.77, df = 2, p = .15$), accuracy ($\chi^2 = 1.60, df = 2, p = .59$), user-friendliness ($\chi^2 = 1.51, df = 2, p = .47$), naturalness ($\chi^2 = 2.52, df = 2, p = .28$), or preference ($\chi^2 = 1.47, df = 2, p = .48$). Fig. 6.17 illustrates the median perceived performance ratings for all conditions in the user study.

6.6 Discussion

Just like in the first study, the finger mouse surpassed both the controller and the thimble in terms of speed, enabling participants to complete scenarios more swiftly. In the teleportation scenario, participants were quicker using the thimble compared to the controller, though the difference was not statistically significant. All devices exhibited high accuracy in both scenarios, with minimal errors during teleportation. This accuracy likely contributed to participants’ favorable opinions of the devices, as reflected in lower frustration ratings. These findings underscore wearable devices’

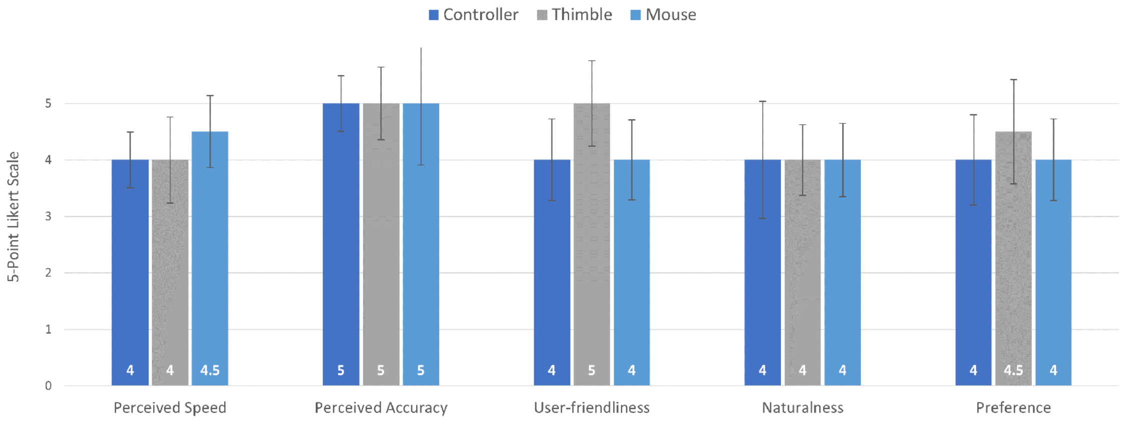


Figure 6.17: The median perceived usability of the user study conditions, rated on a 5-point Likert scale ranging from “1” (strongly disagree) to “5” (strongly agree). Error bars represent ±1 standard deviation.

capability to enhance VR interactions effectively, showcasing the thimble’s potential as a viable alternative for common VR tasks.

Participants consistently praised the thimble for its usability, using terms like *“intuitive”*, *“innovative”*, *“easy”*, *“amazing”*, and *“refreshing”*. They found it straightforward to learn and more comfortable than other devices, reporting lower physical and mental strain. This comfort is likely due to the thimble’s design, which offers support and reduces fatigue compared to holding the controller in mid-air. One participant highlighted the ease of using the thimble and finger mouse on a surface, in contrast to the controller which caused hand strain. Another remarked that the thimble felt like an extension of their hand, improving both comfort and usability. The thimble’s intuitive design was familiar to many, reminiscent of smartphone interactions, easing the transition to using it as an input device. However, one participant favored the controller for tasks requiring vertical movements, attributing this preference to familiarity with controllers in VR settings. This feedback underscores the diverse responses to new input devices, with the thimble offering significant benefits in comfort and ease of use, yet facing challenges in completely replacing controllers for certain tasks.

The teleportation scenario highlighted the value of enabling users to teleport while remaining stationary, proving particularly advantageous in confined settings, such as sitting on a train or airplane. This feature could also aid individuals with limited upper body mobility by adhering to guidelines that advocate for interaction methods requiring minimal physical exertion.

In conclusion, the testing of both scenarios reinforced the effectiveness of wearable devices like the finger mouse and thimble in VR interactions. Although the finger mouse showed superior performance, it still needs improvement to lessen hand strain. The controller, while a valuable tool for VR, may not be the best fit for all situations or prolonged use. Thus, alternatives like the thimble could complement traditional controllers by providing additional comfort and convenience, particularly in restricted environments.

6.7 Conclusion

In this work, we introduced the redesigned digital thimble to interact with virtual environments, employing an optical mouse sensor for tracking finger movements and a pressure sensor for detecting contact force. Through a Fitts' law study and the examination of two prevalent VR scenarios (teleportation and sorting) we showcased the thimble's effectiveness as a versatile input and interaction tool. While the finger mouse, previously unexplored in VR contexts, demonstrated superior quantitative performance, participants notably appreciated the digital thimble for its convenience and comfort during virtual interactions. These findings underscore the potential of finger-wearable devices in VR applications and advocate for further research in this field.

Chapter 7

Summary

This dissertation addressed the core challenges of input and interaction in virtual reality environments, employing cutting-edge haptic and wearable technologies. Our research provides essential guidelines for the refinement of virtual keyboard layouts and showcases the significant enhancements in mid-air text entry facilitated by the incorporation of ultrasonic haptic feedback. Further, we introduced a novel wearable input device, the digital thimble, which offers enhanced precision, comfort, and versatility within virtual reality interactions.

This research begins by addressing the essential task of text entry within virtual reality environments. Virtual keyboards present unique design opportunities, yet the impact of these design choices on user performance and experience remained unclear. A literature review revealed that the absence of physical constraints on virtual keyboards has led designers to experiment with innovative key designs. But the influence of key design on text entry performance and user experience was previously undetermined. We conducted a user study to explore the effects of various key shapes and dimensions on text entry performance and user experience. The findings indicated that key shape significantly influences text entry speed, dimensions impact accuracy, and both factors affect user experience. Notably, square-shaped 3D keys emerged as the top performers in terms of both actual and perceived effectiveness, and were also the most preferred by participants.

Expanding on these findings, we investigated methods to overcome the lack of haptic feedback in mid-air interactions, a common challenge in virtual reality. Freehand mid-air typing, using a Qwerty layout, allows for text input in virtual environments without physical controllers. However, this approach is generally slower and more error-prone compared to traditional typing, primarily due to the absence of tactile feedback and reduced spatial awareness. To address this issue, we focused on integrating ultrasonic haptic feedback to improve mid-air text entry. Ultrasonic haptic feedback is especially suitable for mid-air interactions as it provides tactile sensations without the need for any wearable devices on the user's hands. We developed three types of ultrasonic haptic feedback for mid-air Qwerty typing: feedback on keypress, feedback on both touch and keypress, and gradual feedback that increases in intensity as a key is pressed down. Our initial study showed that the touch and press feedback method significantly outperformed the others in terms of both quantitative and qualitative metrics. Following this, a more comprehensive user study comparing mid-air Qwerty typing with and without touch and press feedback revealed that haptic feedback not only increases entry speed by 16% but also decreases the error rate by 26%. Further, the majority of participants reported that it improved their sense of presence and spatial awareness in the virtual space, making it feel more in line with real-world experiences, while significantly reducing mental effort, strain, and frustration.

Encouraged by these positive outcomes, we broadened our research to include vertical mid-air gestures, which are prevalent in virtual reality and other mid-air interaction platforms, like kiosks. Our review of the literature helped us identify common mid-air gestures, which we then assessed both with and without ultrasonic feedback. We examined four mid-air target selection methods (Push, Tap, Dwell, Pinch) alongside two types of ultrasonic haptic feedback (Select, Hover & Select) through a Fitts' law experiment. The findings indicated that Tap is the fastest, most accurate, and among the least demanding in terms of physical and cognitive effort. Pinch, while fast, tends to be error-prone and more demanding physically and cognitively. Dwell, intentionally the slowest, emerged as the most accurate and least demanding on both counts. The incorporation of either haptic feedback method notably enhances selection performance by boosting users' spatial awareness. In particular, Push combined with Hover & Select feedback matches the efficiency of Tap. Moreover, participants found the selection methods to be perceived as quicker, more precise, and less taxing physically and cognitively when paired with haptic feedback. These results underscore the effectiveness of ultrasonic haptic feedback in augmenting spatial feedback for mid-air interactions, reinforcing its value in these applications.

We then shifted our focus from leveraging existing hardware to exploring the possibilities of developing custom hardware solutions. We opted for wearable devices due to their constant availability and potential for hands-free interaction. To this end, we developed a digital thimble, worn on the index finger, equipped with an optical sensor for tracking movements and a pressure sensor for detecting touch and force. This approach aimed to overcome the limitations of existing VR text entry methods, which are typically slow, prone to errors, stationary, immersion-breaking, or physically taxing. We subsequently developed Shapeshifter to accompany the digital thimble, which facilitates text entry in virtual reality by performing gestures and fluctuating contact force on any opaque, diffusely reflective surface, including the human body. We focused on text entry because existing text entry solutions for virtual reality are either slow and error-prone, stationary, break immersion, or are physically demanding. In a week-long in-the-wild pilot study, Shapeshifter yielded on average 11 wpm on flat surfaces (e.g., a desk) and 9 wpm on the lap when sitting down, and 8 wpm on the palm and back of the hand when standing up in text composition tasks. A simulation study predicted a 27.3 wpm error-free text entry rate for novice users in transcription typing tasks on a desk. These results suggest that Shapeshifter can outperform common gesture typing devices in virtual reality, whilst being intuitive and natural to use. These promising early results with the digital thimble encouraged us to explore its broader applications within virtual reality.

Therefore, we redesigned and assessed the digital thimble specifically for free-hand interactions within virtual reality environments. Initially, we conducted a Fitts' law study to compare the digital thimble with a commercial wearable finger mouse (previously unexplored in virtual reality contexts) and a traditional controller, using two selection methods: press and touch-release. Subsequently, we further investigated the thimble's and finger mouse's performance in sorting and teleportation scenarios through a second user study. While the finger mouse demonstrated superior throughput and task completion speed, the digital thimble showed greater accuracy and precision. Participants also favored the digital thimble for its enhanced comfort and convenience, underscoring its potential as an efficient, comfortable, and user-friendly input device for virtual reality applications.

In conclusion, this work comprehensively addresses input and interaction challenges within virtual reality environments through the exploration of haptic feedback and the development of a novel wearable device. We established guidelines for virtual keyboard design, demonstrating the significant impact of key shape and dimensions on both performance and user experience. The integration of ultrasonic haptic feedback proved remarkably effective in enhancing midair text entry, accuracy, and user experience across both horizontal and vertical gestures. Furthermore, our custom-designed digital thimble exhibited significant potential as a precise, comfortable, and versatile input solution for VR interactions. We believe the thimble's compact design makes it ideal for confined places like planes and trains, expanding the potential use cases and overall accessibility of virtual reality. This research offers valuable insights into the design of efficient and user-centered input methods, ultimately paving the way for more immersive and seamless virtual reality experiences. The findings presented here have the potential to revolutionize how we interact with virtual worlds, making them more responsive, accessible, and intuitive.

7.1 Future Work

In the future, we will further develop the thimble's functionality, we intend to incorporate haptic feedback and integrate additional sensors, including inertial measurement units. These enhancements are expected to broaden the thimble's applicability across a wider range of virtual reality scenarios. Moreover, we plan to investigate various user postures and methods of interaction to enhance the thimble's adaptability and ease of use within virtual environments. We will also employ machine learning to create sophisticated input prediction, surface prediction, and gesture recognition models, making the thimble even more versatile. Our ongoing research is dedicated to advancing the design and utility of finger wearables for virtual reality applications, aiming to create a more immersive and intuitive user experience. Finally, to further optimize ultrasonic haptic feedback, we will conduct a systematic investigation of various haptic patterns and durations. Our goal is to identify the most effective combinations for different virtual reality interactions, maximizing feedback clarity, intuitiveness, and user satisfaction through rigorous empirical evaluation.

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