EVALUATION OF HUMAN-MACHINE INTERFACES WITH VARYING HAPTIC FIDELITY LEVELS IN AR/VR APPLICATIONS

by

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To my mother and father, my grandparents in heaven, and to my fiancée Raneem,

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I am deeply grateful to my advisor, Prof. Osamah Rawashdeh, for his guidance, high standards, and unwavering support from the first ink drop to the final page, and to Prof. Wing-Yue Geoffrey Louie for incisive critiques and practical advice that sharpened my methods and analysis. I also thank the students of the Embedded Systems Research Lab, whose diligence in running study sessions and sustained contributions to development made this work possible.

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My heartfelt thanks go to my friend Ahmad Albawaneh (Ph.D. candidate), who kept me going. Making sure I ate, checking in when the days were long, and reminding me there is light at the end of the tunnel.

I owe the deepest personal thanks to my family: to my late grandmother, whose memory sustained me when the distance felt longest, this milestone is for her. To my mother, who would not sleep until she heard my voice. To my fiancée, Raneem, whose patience and determination carried our plans forward. And to my father, whose early encouragement helped launch my career in the United States, through difficult moments, that foundation still mattered.

Fares Tareq Al-Shubeilat

PREFACE

This thesis rose from a simple observation of the increasing capability of head-mounted displays and spatial interfaces that still rely heavily on seeing and hearing, while touch *(the sense we rely on to manipulate the world)*, remains underrepresented. Bridging that gap requires evidence about when richer haptics matter and when they don't. The study reported here was designed to provide such evidence by comparing three haptic fidelity levels (no haptic fidelity gloves, low haptic fidelity gloves, high haptic fidelity gloves) against a physical touchscreen on a set of familiar, ecologically meaningful gestures. It combines methods together from computer engineering and human-computer interaction to evaluate both how users feel in VR (presence, embodiment, usability) and how well they perform (accuracy, errors, timing, and speeds).

A key aim was to move beyond single-device demonstrations to ask haptic fidelity questions at the gesture level. Tap, swipe, pan, and pinch gestures are essential gestures to navigate on modern touchscreen and human-machine interfaces. Additionally, a combinational task approximates a realistic touchscreen workflow that mixes discrete and continuous actions. By anchoring every haptic fidelity condition to a real-world touchscreen baseline, the study separates improvements attributable to haptic realism from limits imposed by end-to-end tracking and rendering latency. Such framing allows us to translate the findings into actionable guidance for engineers and designers who must balance, cost, comfort, and complexity when selecting haptic systems for training, prototyping, and operational use.

The thesis is organized to be read either linearly or by interest. The opening chapters introduce the problem space, survey touch and haptic technologies, and motivate the haptic fidelity framework adopted here. The methodology explains the between-subjects design, apparatus, tasks, and measures. Meanwhile for the results chapter, it reports the assumption checks and statistical outcomes for subjective and objective measures. The discussion interprets the findings found in the results chapter in further detail, integrates theoretical implications, and provides practical guidelines, limitations, and future directions. Lastly, the concluding chapter gives the main contributions and outlines how these findings can inform the next generation of AR/VR human-machine interfaces.

I hope this work helps practitioners choose the correct haptic fidelity for their job, inspires further research that pairs advances in devices with careful measurement of human performance and experience.

ABSTRACT

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Adviser: Osamah Rawashdeh, Ph.D.

This thesis evaluates how varying haptic fidelity levels shape the user experience and performance in gesture-based touchscreen interactions conducted in immersive VR. A between-subjects design compared the four conditions: a benchmark of real-world tablet touchscreen and three VR configurations, no haptic fidelity (hand tracking only), low haptic fidelity (vibrotactile gloves), and high haptic fidelity (tactile + force feedback). The participants completed touchscreen tasks (tap, swipe, pan, pinch) and a combinational task while subjective outcomes (presence, embodiment, and system usability) and objective performance metrics were recorded. The study answers three questions: (i) whether haptic fidelity alters perceived experience, (ii) how fidelity influences task performance, and (iii) which gestures are most sensitive to the haptic fidelity. The results show that perceived metrics were indistinguishable across the three haptic fidelity conditions, suggesting high quality consistent visuals/interactions dominated over the incremental in the touch cues richness at the fidelities tested.

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LIST OF ABBREVIATIONS

VR	Virtual Reality
AR	Augmented Reality
GAO	Government Accountability Office
HMI	Human-machine Interface
HMD	Head Mounted Display
HCI	Human-Computer Interaction
HX	Haptic Experience
RHI	Rubber Hand Illusion
VHI	Virtual Hand Illusion

CHAPTER ONE

Introduction

Virtual Reality (VR) and Augmented Reality (AR) are very promising tools for rapid prototyping and testing. VR and AR enable immersive, real-time simulation of products and designs without the need for physical production and fabrication. Figure 1 illustrates that it does significantly reduce development time, cost, and iteration cycles, while allowing for early detection of flaws in a realistic context. In 2023, the BMW Group revealed the plan to open the Digital iFactory, which is a virtual digital twin to the Debrecen Plant [1]. In 2024, the U.S. Government Accountability Office (GAO) surveyed 23 federal civilian agencies and found that 17 agencies reported using immersive technologies like VR and AR during the 2022-2023 fiscal years [2]. Additionally, 16 agencies plan to expand their use of immersive technologies between 2024 and 2028 fiscal years in areas like design, planning, and remote collaboration [2]. Figure 2 provides a summary of number of agencies engaged with immersive technology during 2022-2023, distinguishing between those that used immersive technology, conducted researched and developed, or did both. Similarly, Figure 3 presents the projections for 2024-2028.

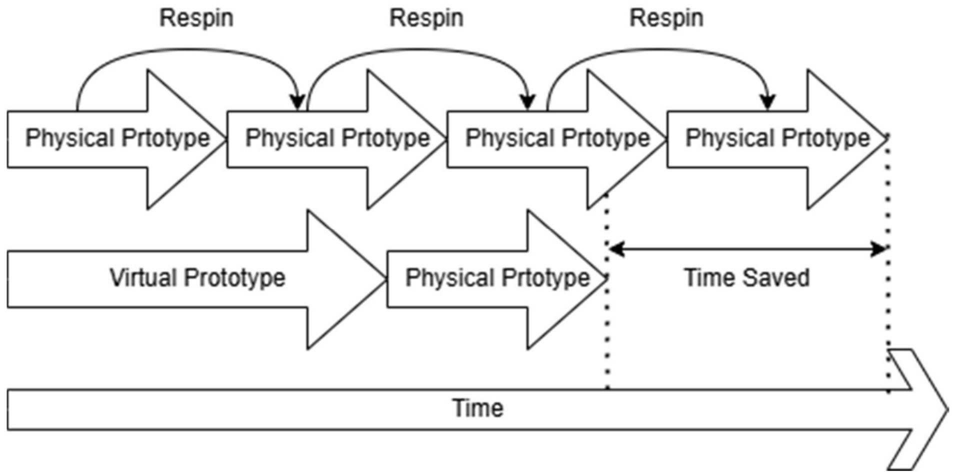

Figure 1 - Reduced Amounts of Physical Prototype Respins

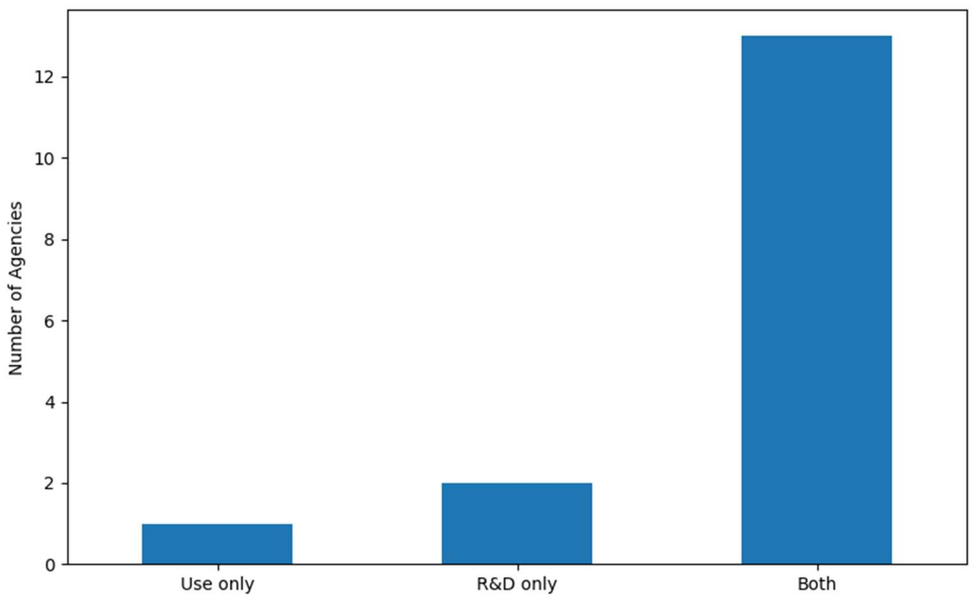

Figure 2-Agency Current Participation in Immersive Tech (2022–2023)

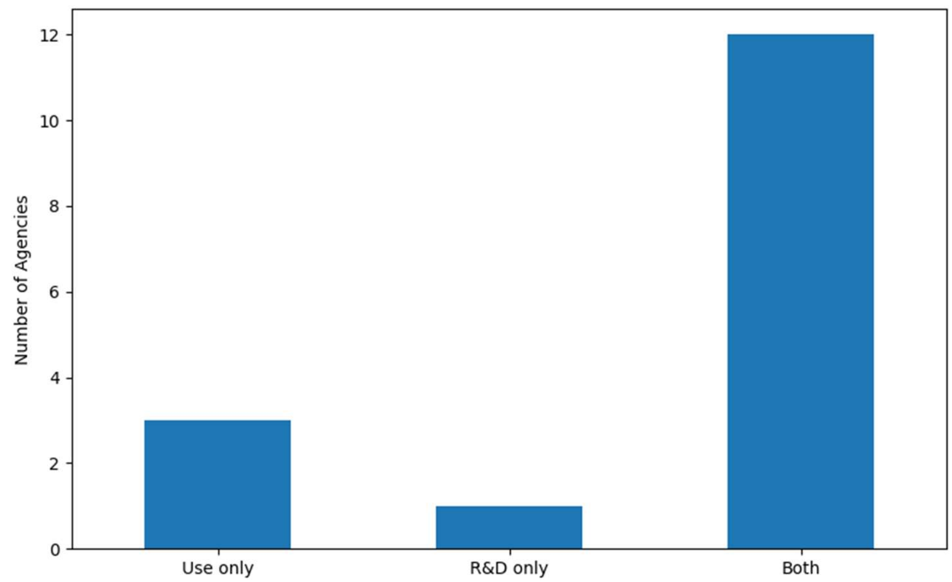

Figure 3-Agency Planned Participation in Immersive Tech (2024–2028)

Tablet touchscreens are a common Human-machine Interfaces (HMIs), enabling the user to interact with graphical elements such as buttons, sliders, and virtual keyboards and keypads using their natural hand gestures. The support of portability and multi-touch capabilities makes tablets ideal for controlling and navigating digital systems in applications ranging from healthcare, to industrial automation, education, and defense. The Research and Markets report titled *Touch Screen Market 2024-2028* forecasts a projected growth of 17.3 billion between 2023 and 2028. The surge is caused by the wide integration of touchscreen technology across diverse sectors [3] [4].

Virtual touchscreens are interactive displays that replicate the behavior of physical touchscreens without requiring direct physical contact. These systems typically rely on computer vision, and motion sensors to detect finger positions and gestures in 3D space. Early developments in virtual touchscreen technology can be traced back to research in optical gesture tracking in the late 1990s [5], with commercial products emerging in the 2010s through devices like the *Leap Motion Controller* and *Xbox Kinect*.

In recent days, the advancements are being poured into AR and VR environments, by pushing an evolution of virtual touchscreens into spatial interfaces that are rendered via HMDs or projection-based AR systems. These interfaces are increasingly adopted in fields like automotive Heads Up Displays (HUDs), gaming whether using VR or motion tracking systems like the Kinect, and public kiosks.

VR and AR technologies including Head Mounted Displays (HMDs) primarily rely on conveying information through the visual system and, in some cases, the auditory system. The use of HMDs for VR through video and audio transmission only, neglects the use of the other senses, smell, taste, and touch. In particular, the absence of touch negatively impacts the levels of immersion and realism of the user's experience in VR. Haptic feedback devices address this limitation by interacting with the sense of touch, which enables users to physically feel virtual world objects through vibration, force, and tactile sensations. Such devices improve the levels of immersion and realism by providing touch sensory cues that align with the visual and auditory cues.

As the use of HMDs expands into fields like training, rehabilitation, prototyping, and design evaluation, the integration of haptic feedback becomes more of a necessity to achieve the required level of effective user experience. Wang et al. introduced a low-cost haptic feedback device that simulates the weight and center of gravity of virtual objects. Their findings included that the user's level of immersion and experience can deteriorate with the absence of haptic feedback. Moreover, the participants reported a higher level of presence in terms of realism when haptic feedback was incorporated [6].

The integration of haptic feedback and expanding the methods of sensory reception offers a unique experience that aims to promote deeper engagement and expands their sensory interaction during training, leading to increased engagement, more accurate skill acquisition, and better retention of learned tasks in simulated environments [7]. As haptic technology continues to develop, researchers are increasingly focused on improving the realism, responsiveness, and ergonomic integration of these systems [8]. Wearable haptic devices, such as gloves and exoskeletons, have been designed to mimic fine-grained tactile responses including texture, temperature, and pressure. These advances aim to replicate natural hand-object interactions in VR, making tasks more authentic and intuitive. Such capabilities are particularly important in hands-on fields where precision is critical, such as surgical training, combat simulation, and remote manipulation [9]. Despite these advancements, challenges remain in balancing cost, comfort, and computational efficiency, driving ongoing research into scalable, high-resolution haptic systems for real-world deployment.

To evaluate the effectiveness of VR systems, researchers use subjective and behavioral measures such as presence, embodiment, and system usability [10] [11] [12]. Presence refers to the user's psychological state of "being there" within the virtual environment, reflecting how convincing the system simulates reality [13]. Embodiment measures how much the user feels that their virtual body or virtual body parts are their own, which is critical in tasks that focus on ownership, agency, and change [14]. Moreover, system usability evaluates the overall efficiency, effectiveness, and user satisfaction with the VR setup [12]. Together, these measures provide an understanding of how effective, engaging, and practical the VR experience is, especially when evaluating experimental technologies and techniques such as haptic feedback.

To better investigate how haptic feedback impacts the user's experience in VR, it is important to delve into the anatomy of touch. In specific, how the tactile information is processed by the human body.

The sense of touch, also known as somatosensation, is primarily mediated by sensory receptors embedded under the skin called mechanoreceptors. As shown in Figure 4, these receptors named Merkel cells, Meissner's corpuscles, Ruffini endings, and Pacinian corpuscles, are each made to detect different types of mechanical stimulation that is found in touch such as pressure, vibration, stretch, and texture [15]. When the mechanical stimuli is active, these mechanoreceptors convert mechanical input into sensory signals that are transmitted via peripheral nerves to the spinal cord and then to the somatosensory cortex of the brain [16]. Though often underestimated, the sense of touch enables these mechanoreceptors not only allow humans to perceive the presence of contact, but also the shape, temperature, texture, weight, and the dynamic properties of objects [17]. Therefore, the understanding of the anatomy of touch allows us to design haptic feedback systems that accurately simulate a naturalistic sense of touch in virtual environments.

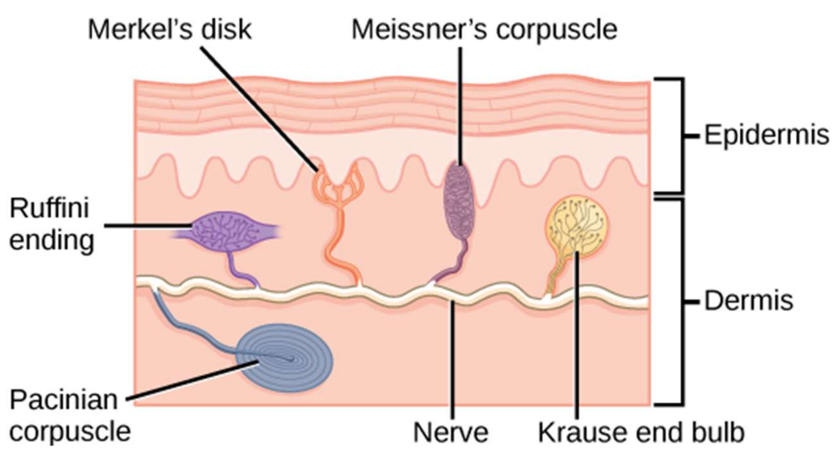

Figure 4-Primary Mechanoreceptors in Human Skin (Credit to LibreTexts Biology)

1.1 Motivation

This study offers a unique opportunity to understand multiple domains, virtual reality, human-computer interaction (HCI), and haptic technology. With the rise of VR especially HMDs, there is growing demand for a more immersive and effective interaction beyond the more common visual and auditory modalities. While VR is advancing in the more common visual and auditory modalities, the sense of touch seems underrepresented, yet it is a fundamental to achieve better realism and immersion. By investigating how varying fidelity levels of haptic feedback influences the user experience in interactive virtual environments, this work aims to contribute to the better understanding of multisensory VR integration and to the practical development of more effective simulation, training, rapid prototyping, and testing.

The VR industry has been witnessing a significant advancement in terms of display resolution, which improves an important factor, visual fidelity. This factor influences the user's immersion and comfort. The higher resolution also reduces the screen-door effect, which is when the user perceives a grid of lines caused by the space between individual pixels [18]. Minimizing this effect would lead the user to experience smoother edges, clearer textures, and finer details in virtual environments, which are essential in some applications requiring high visual precision such as surgical simulations and industrial design evaluations. The VR industry did not only advance in display resolution, it has also improved in the accuracy of tracking [19] and processing power [20], which all contribute into a more immersive and realistic virtual experience. Precise tracking systems ensure that users' movements, including head and body, are accurately mirrored in real time, reducing the chances of the user experiencing disorientation and motion sickness [21]. In fact, motion sickness arises from a mismatch between the HMD's visual inputs and the vestibular sensations, which are the signals from the inner ear that help the brain detect spatial orientation, balance, and motion [22].

Touch is a fundamental human sense that plays a critical role in how we perceive, interact, and interpret the physical world. In virtual environments, the absence of haptic feedback can lead to a perceptual disconnect, reducing the effectiveness of simulations [23]. Haptic technologies attempt to replicate the sense of touch through various methods, for example, vibrotactile actuators that simulate the textures of virtual objects or impacts with them, force feedback that recreates resistance and the weight of objects, and even through electrostimulation of the nerve endings to send the signals of interacting with objects [6]. Such technologies aim to mimic the physical interaction with objects like grasping, pressing, tapping, or encountering resistance in ways that feel natural and convincing to users.

Gesture-based tasks are particularly relevant in this context, as they require users to perform natural, embodied interactions that heavily rely on the tactile response and feedback for precision and realism. Gestures are considered to be an active form of touch. Unlike passive forms of interaction, it involves real-time sensorimotor feedback loops, which amplifies the perceptual impact of different haptic fidelity levels [24]. Existing research has often focused on isolated modalities of haptic feedback, such as force feedback or vibrotactile cues, but few studies have evaluated the holistic impact of haptic fidelity on the user experience across gesture-based tasks. This gap presents an opportunity to investigate the correlation between haptic fidelity and the haptic user experience.

While the prior research has explored haptic cues in isolation or within restricted application contexts, there is limited understanding of how varying levels of haptic fidelity, when applied on a set of gesture based interactive tasks, influence the user's experience. This is not limited to the sensory realism but also the cognitive and behavioral outcomes like embodiment, presence, overall system usability, and in-task performance.

To address this gap, this study is guided by the following research questions:

- **RQ1:** *How do varying levels of haptic fidelity impact user presence, embodiment, and system usability in gesture-based VR tasks?*
- **RQ2:** *How do different haptic fidelity levels influence performance metrics such as accuracy, error rate, speed, and task completion time?*
- **RQ3:** *Are continuous gestures more sensitive to differences in haptic fidelity compared to discrete gestures?*

This study explores how varying haptic fidelity levels, ranging from no haptic fidelity to high haptic fidelity, affect the user-reported presence, embodiment, system usability, and performance metrics across touchscreen gesture-based tasks in a virtual environment. Participants are assigned to one of four haptic conditions, including a real-world control group and three varying levels of haptic fidelity in VR. All four groups will be performing the same set of touchscreen gesture-based tasks, including touchscreen gestures like tap, pan, pinch, swipe. This between-subjects design allows for comparison across different fidelity levels to evaluate their effectiveness using the previously mentioned haptic user experience criteria.

1.2 Background

The advancement of VR, AR, and immersive technologies has transformed how humans interact with digital content, moving beyond traditional peripheral-rich, screen-based interfaces toward multisensory, embodied experiences. Since the introduction of early versions of HMDs, beginning with the Telesphere Mask in 1960s and the subsequent development of haptic feedback devices with the Force-Reflecting Hand Controller in the 1990s, immersive systems have progressed toward increasingly naturalistic forms of interaction [25] [26]. Over time, both research and industry have steadily advanced platforms capable of mimicking the complex interactions of the real world. Haptic feedback interfaces have significantly advanced in this pursuit, they are systems that are designed to simulate the sense of touch through physical feedback mechanisms such as vibration, pressure, and force resistance. These systems are often categorized based on their level of realism, commonly referred to as haptic fidelity, which describes how accurately a device replicates the tactile and kinesthetic sensations [27].

As the immersive environments shift from being observed passively to being manipulated actively, for example, gesture-based input, the fidelity of haptic feedback becomes increasingly critical. Unlike traditional input methods such as keyboards or mouse clicks, gestures involve dynamic, continuous sensorimotor loops where users depend on tactile cues to guide their accuracy, timing, and control. As this interaction paradigm evolves, it puts new demand on haptic systems to respond authentically, replicating the spatial, temporal, and mechanical characteristics of real touch.

1.2.1 The Anatomy of Touch

Achieving realistic haptic feedback in virtual environments requires more than just technical replication; it requires alignment with how the human body's natural sensory system operates. The skin, muscles, and joints contain specialized receptors that detect mechanical pressure, temperature, and even pain.

As previously mentioned, the major mechanoreceptors, Merkel cells, Meissner's corpuscles, Ruffini endings, and Pacinian corpuscles are responsible for detecting mechanical stimulation such as pressure, stretch, and vibration [15]. While these mechanoreceptors have many functionalities, they represent only part of the somatosensory system. As shown in figure 5, these receptors are found more commonly in *glabrous skin*, such as the palms and fingertips of the hands, as well as the soles of the feet, which enables us to have fine tactile discrimination and object manipulation using these parts of the skin. In contrast, *hairy skin* instead relies more on hair follicles for sensitivity as it contains less mechanoreceptors, making it less precise but still responsive to touch [15].

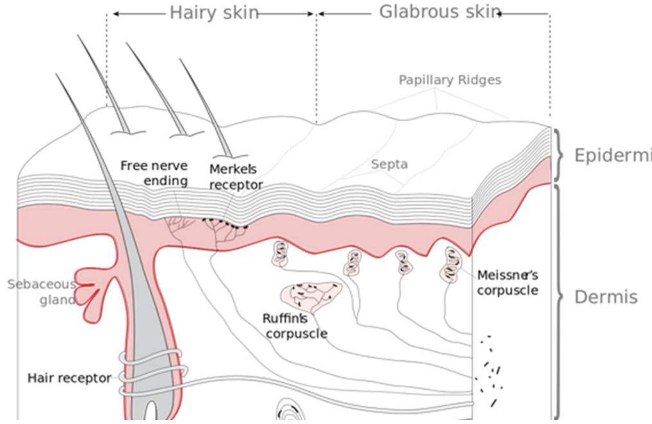

Figure 5- Receptors Associated with Glabrous and Hairy skin. Original image by Thomas Haslwanter [56]

Mechanoreceptors are usually categorized by how fast they respond to stimuli, often referred to as the *adaptation rate*. Fast-adapting receptors respond transiently to changes in stimulus, detecting motion and vibration. Slow-adapting receptors provide continuous feedback as long as contact is sustained, allowing for the perception of shape, skin stretch, and steady pressure. These types of responses are critical for simulating realistic tactile feedback in haptic systems, not only to replicate the spatial characteristics of objects but also their temporal dynamics as well [28].

In addition to adaptation rate, mechanoreceptors are also distinguished by their receptive fields, which is size and the area of skin from which they receive input [28]. Mechanoreceptors like Merkel cells and Meissner's corpuscles have a small, well-defined receptive fields, making them ideal for detecting fine details such as edges, points, and surface textures [29]. Small receptive field mechanoreceptors are most effective in regions requiring high tactile acuity, like the fingertips. On the other hand, Pacinian corpuscles and Ruffini endings have broader receptive fields, allowing them to detect vibrations and stretch across larger area of the skin [15]. This categorization helps us in how densely and where actuators must be placed in wearable haptic systems. A summary of these mechanoreceptors, including their adaptation rate, receptive field size, and function, is provided in Table 1.

Table 1- Characteristics of Primary Mechanoreceptors in Glabrous Skin

Receptor Type	Adaptation Rate	Receptive Field Size	Primary Function	Typical Location
Merkel Cells	Slow-Adapting	Small	Pressure, edges, form, texture	Fingertips, lips, palms
Meissner's Corpuscles	Fast-Adapting	Small	Light touch, motion detection	Fingertips, eyelids, palms
Ruffini Endings	Slow-Adapting	Large	Skin stretch, sustained pressure	Skin over joints, palms
Pacinian Corpuscles	Fast-Adapting	Large	High-frequency vibration, sudden disturbances	Fingers, joints, tendons

Other than the skin, proprioceptors include muscle spindles, Golgi tendon organs, and joint capsule receptors [30]. As summarized in table 2, such proprioceptors provide internal feedback about limb position, tension, and movement which are. The internal sensation of the body's position and motion is referred to as *proprioception*, and its movement specific component is known as *kinesthesia*, which is the signals sent to muscles and joints to perform voluntary movement [31]. Combined together, the brain is able to maintain spatial awareness and perform coordinated movements without visual inputs. Proprioception enables sensorimotor integration, linking intention, motion, and feedback into a closed control loop [31]. In haptic systems, proprioceptive cues are essential for tasks that involve resistance, grasp, force modulation, allowing engineers to design better force feedback systems for wearable technology.

Table 2- Mechanoreceptors vs. Proprioceptors

Category	**Mechanoreceptors**	**Proprioceptors**
Stimuli	External Stimuli	Internal Stimuli
Types	Merkel's disks, Meissner's corpuscles, Ruffini ends, Pacinian corpuscles.	Muscle spindles, Golgi tendon organs, Joint capsule receptors
Distribution	Primarily in skin	Primarily in the muscles and tendons

In anatomy, kinesthetic feedback is the user's perception of movement, force, and resistance through muscles and joints. When kinesthetic feedback is technically implemented, it is referred to as force feedback, where mechanical resistance is applied by actuators to represent the physical properties of objects, like weight and inertia [32]. Contrary to the tactile feedback which actuates the skin, kinesthetic feedback involves sensors that are responsible for motion and load perception.

These biological systems do not function in isolation; but rather the work in continuous coordination, allowing humans to perceive, interpret, and respond to stimuli with precision and intent. Technical sophistication is required in order to replicate this complex interplay virtually. This knowledge directly informs actuator selection, actuator placement strategies, and timing of actuation in wearable haptic feedback devices, ultimately guiding how artificial stimuli can be engineered to feel both natural and functional. In the following sections, we will explore how current haptic technologies attempt to stimulate the sensory mechanisms and how we categorize these technologies based on what is called haptic fidelity.

1.2.2 Haptic Devices Classification

As discussed earlier, the human sense of touch is composed of multiple sensory channels, all contributing to the perception and interpretation of physical interactions. According to Muender et al., haptic fidelity refers to how much the haptic system can replicate the sensory experiences of touch accurately and convincingly [27]. This framework asses the device's haptic fidelity based on the fourteen factors listed in figure 6 on a spectrum that ranges between abstract and realistic. Therefore, the classification of haptic devices based on their haptic fidelity aids in the comparison of different technologies offered, understanding their limitations, and the correct product selection for specific interaction goals. Ultimately, the devices' goal is to perfectly replicate natural interactions with high-fidelity devices aiming to reproduce the full tactile and kinesthetic spectrum with high realism. On the other hand, lower fidelity systems try to simplify or abstract the sensations for multiple reasons, including cost,

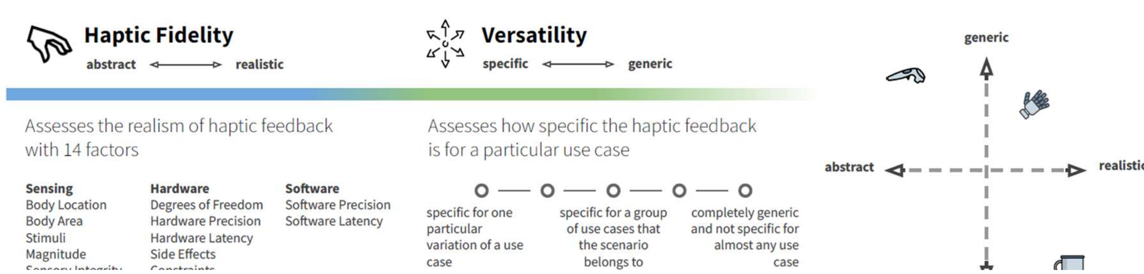

Figure 6- Haptic Fidelity and Versatility Spectrums [27]

hardware, or computational constraints. Another aspect that the framework considers is versatility, which assess how specific the device is for a particular use case.

Haptic devices that have tactile feedback are designed to simulate the skin's surface, by targeting the mechanoreceptors responsible for sensing vibration, pressure, texture, and skin stretch. There are many ways to resemble touch in tactile feedback, these devices more commonly use vibrotactile actuators [33] (Figure 7), compressed tactile actuators [34](Figure 8), or fluid actuation [35] (Figure 9). Meanwhile haptic devices with force feedback provide external mechanical forces to the muscles and joints, which simulates physical properties such as weight, resistance, or inertia. Such devices usually represented as external robotic arms [36] (Figure 10), exoskeletons [37] (Figure 11), or cable-based brake actuation [38] (Figure 12). Moreover, some devices like the HaptX G1 and Teslasuit Teslaglove, integrate both feedbacks into their devices to provide higher realism and thus having a higher fidelity level.

While high-fidelity device manufacturers claim providing highly realistic feedback, they often come with trade-offs in terms of bulkiness, weight, cost, and energy consumption. Wearable and portable devices usually sacrifice fidelity to improve usability and comfort. On the other hand, grounded systems like large robotic arms could achieve precise kinesthetic feedback but lacks general accessibility and mobility. Big firms and companies must understand these trade-offs for selecting or designing haptic systems.

Figure 7- Vibrotactile Actuated Bhaptics Tact Glove DK2

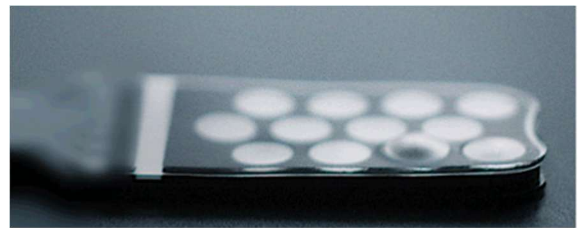

Figure 8- Compressed Tactile Actuator Found in HaptX DK2 Glove Fingertips

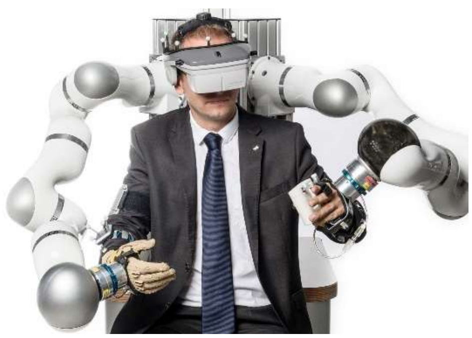

Figure 10-HUG Robot for Force Feedback

Figure 9-Fluid Reality's Fluid Actuated Tactile Feedback

Figure 11- Teslasuit Gloves with Force feedback Exoskeleton

Figure 12- Wireality's Cable-based Brake Actuation

1.2.3 Evaluation Metrics for VR Experiences

Evaluating user experiences in virtual environments requires a combination of subjective and objective measures to assess how convincingly and effectively a system replicates real-world interactions. Among the widely adopted measures for assessing the Haptic Experience (HX) are *presence*, *embodiment*, *system usability,* and *performance*, each measure offers unique insights on how the system supports natural interaction.

Presence is described as the psychological state in which users feel they are "inside" or part of the virtual environment, rather than observing it. High levels of presence indicates that the sensory channels inputs and interactions in the VR system aligns with the user's perceptual and cognitive expectations, creating a convincing experience. Presence levels depend on the influencing factors, such as visual fidelity, latency, interaction, realism, and the availability of multisensory feedback using haptics. This study aims to measure how the addition of different modalities of tactile feedback and force feedback can affect the presence scores, especially that it provides touch cues that match the user's proprioception and the displayed visual input. Presence is typically evaluated using established instruments such as the Witmer and Singer Presence Questionnaire, the Slater-Usoh-Steed Questionnaire, or the Igroup Presence Questionnaire; the study utilizes the Igroup Presence Questionnaire for this purpose.

Embodiment is an extension to the concept of presence by focusing on the user's ownership and control of a virtual body avatar. Embodiment encompasses three main components:

- *Body ownership*: The feeling that the virtual body parts or avatar are one's own.

- *Agency*: The user's sensation of controlling the virtual body parts or avatar and their expected outcomes.
- *Change*: The perceived change of the user in the body scheme.

The high sense of embodiment aids in the decision making of the necessary haptic fidelity levels for tasks that require fine moto skills, tool use, and social interactions. In addition, the sense of embodiment gives an opportunity to investigate trends of performance as embodiment is directly to performance in many domains, such as motor skill learning, emotional regulation, and physical activities. One classic example of embodiment is Botvinick & Cohen's Rubber Hand Illusion (RHI) experiment, which illustrates the mechanisms of body ownership [39]. In their experiment, a participant's real hand is hidden from view, while a rubber hand is visible to them, as demonstrated in figure 13. When the real and rubber hand are stroked synchronously, participants often begin to feel the rubber hand is part of their own body. Such experiments demonstrate how the brain includes visual and tactile information to have a sense of ownership, even on non-biological objects. Similarly, with technology advancements, the Virtual Hand Illusion (VHI) experiment was conducted by researchers as shown in figure 14.

System usability is a measure of user's overall efficiency, effectiveness, and satisfaction of the system. Traditionally, system usability is measured using the System Usability Scale (SUS), which gives an insight on how the acceptable and feasible the system implemented is, especially with the complexity that comes with high haptic fidelity systems.

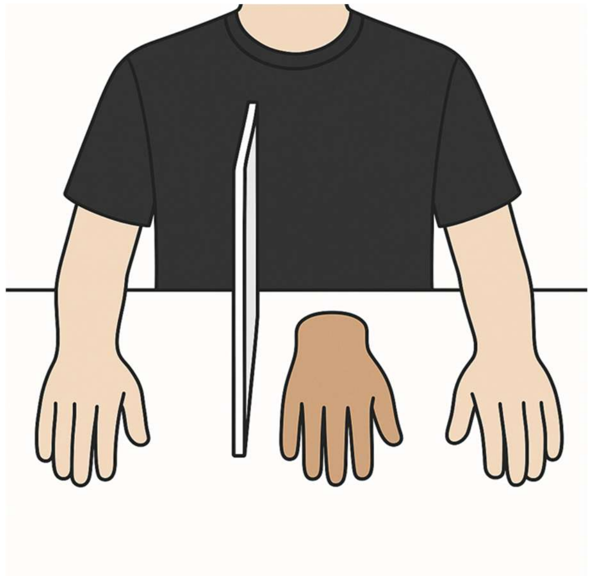

Figure 13 - Rubber Hand Illusion (RHI)

Figure 14 - Virtual Hand Illusion (VHI)

Beyond the previously mentioned subjective measures, performance offers an objective measure on how well the VR system support the user in performing the tasks. In this study, performance includes real- time logged task completion times, accuracy rates, and derived data such as speeds and error rates.

Together, the mentioned subjective and objective measures provide a comprehensive framework for analyzing the effectiveness of VR systems. In this study, these metrics are key indicators for the assessment of how varying haptic fidelity levels influence touchscreen gesture-based interactions.

1.3 Contributions

This thesis contributes to the research on Human-Computer Interaction (HCI) in immersive environments by providing both theoretical and practical insights on the role haptic feedback. The major contributions are summarized as follows:

Systematic comparison of haptic fidelity levels

The study offers a controlled evaluation across four conditions: no haptic feedback, low haptic feedback, high haptic feedback, and a real-world control. Unlike prior research which concentrated on investigating the modalities in an isolated environment or using single devices, this study enables a direct comparison between fidelity levels under identical task conditions.

Integration of subjective and objective evaluation methods

This work combines validated questionnaires that evaluate presence, embodiment, and system usability with logged performance metrics, including accuracy, error rate, speed, and task completion time. The mixed-methods approach allows for a comprehensive understanding of how haptic fidelity influences the user experience in VR.

Gesture-specific analysis of fidelity levels

The examination of both discrete gestures (tap, swipe) and continuous gestures (pinch, pan) allows for the identification whether certain types of interaction are more sensitive to different haptic fidelities. This method contributes to design knowledge on how fidelity requirements vary across interaction types.

Practical guidance for VR/AR system design

The findings of this study inform developers, researchers, and engineers about when high haptic fidelity systems are essential for their application, and when a lower fidelity or no haptic feedback may be sufficient. Such insights are helpful in applications like training, prototyping, rehabilitation, and remote collaboration. These applications tend to balance cost, scalability, and usability.

CHAPTER TWO

Literature Review

2.1 Human-Computer Interaction in VR/AR

The field of Human-Computer Interaction (HCI) is experiencing an evolution, transitioning from traditional peripheral input devices such as mice and keyboards to touchscreens, and more recently to gesture-based spatial interfaces. The timeline of this evolution shows a trend toward more natural and intuitive forms of interaction, where the user's body becomes the primary medium of input. Virtual and Augmented reality (VR/AR) extend this evolution further by emphasizing embodied interaction, enabling users to engage and interact with digital environments through physical movement, head orientation, and spatial gestures. However, despite the shift, most common forms of VR/AR systems rely heavily on visual and auditory modalities, often neglecting the sense of touch and its tactile feedback. This imbalance limits the sense of realism and immersion, leaving the sense of touch underrepresented, even though the human interaction with the physical world heavily relies on it.

2.1.1 Industrial/Training Applications

The use of virtualizing technology in industrial and training contexts has been widely explored in the literature, with studies consistently reporting benefits such as increased immersion, improved skill acquisition, and reduced costs. Huang et al. demonstrated in wildfire training simulations that higher levels of immersion and resolution increased participants' concentration and presence, suggesting that visual fidelity alone can significantly affect the learning outcomes [40]. Similarly, Tsukada et al. conducted a randomized clinical trial on Personal Protective Equipment (PPE) training and showed that VR-based training can match the effectiveness of in-person training. VR-based training also outperforms video-based training in knowledge retention and task accuracy [41]. Such findings show the potential of VR as a reliable substitute for traditional training methods, particularly in scenarios that are hazardous, resource-intensive, or with constrained logistics.

A particularly novel industrial example is found in the commercial vehicles factories of Volkswagen, where Volkswagen was able to deploy VR training with haptic feedback gloves. The training consisted of an assembly task for the vehicle door, trainees used the *SenseGlove Nova* to grasp and manipulate virtual components such as cables, drills, and interlocking parts. Trainers reported that the trainees found it more realistic to work with SenseGlove Nova against working with a joystick/controller [42]. This case study shows that the application of haptic feedback helps in increasing task naturalness and training effectiveness in industrial environments.

From a HCI perspective, academia further suggests that the implementation of haptic feedback enhances realism and task performance by extending beyond the classical visual and auditory modalities. Wang et al. introduced a device named *VibroWeight*, which simulates the weight and the center of gravity of virtual objects. From their findings, it has been reported that participants experienced a reduced level of presence and immersion when haptic feedback was absent [6]. Likewise, Hwang et al. explored industrial training with vibrotactile and pseudo-haptic simulation, showing that tactile augmentation improved learning outcomes [43]. These studies suggest that haptic feedback is a central modality rather than it being an accessory.

Despite the advancements, most prior work has investigated isolated forms of haptics (e.g. vibrotactile only) within narrowly defined tasks, as summarized in Table 3. There remains limited understanding of how different levels of haptic fidelity levels of haptic devices influence both subjective user experience and objective task performance. Addressing this gap is a core objective of this Thesis.

Table 3- Prior VR Training and Industrial Applications of Haptics

Study	Application	Factors Tested	Key Finding	Limitation
Huang et al. [40]	Wildfire training	Immersion level, visual resolution	Higher immersion and resolution improved presence and engagement	Focused only on visual fidelity; no haptics tested
Tsukada et al. [41]	PPE training	VR vs. in-person vs. video	VR ≈ in-person effectiveness; better than video training	Training domain limited to healthcare; no haptics
Wang et al. [6]	VibroWeight device	Weight & center-of-gravity simulation	Haptics improved realism and sense of presence	Pseudo-haptics only; no fidelity spectrum
Hwang et al. [43]	Industrial training	Vibrotactile & pseudo-haptics	Increased engagement and skill acquisition	Narrow task scope; no fidelity variation
VW Case Study [42]	Automotive assembly	Haptic Feedback Gloves	Trainees reported higher realism vs. controllers	Industrial case report; not controlled experimental data

2.1.2 VR HMIs & Gestures

Touch-based interaction has become one of the most widespread modalities in modern Human-machine Interfaces (HMIs), enabling users to interact with graphical elements on the screen such as buttons, sliders, and virtual keyboards through natural gestures like tapping and panning. Physical tablets and touchscreen interfaces are already widely adopted in many domains such as automotive dashboards, industrial control systems, healthcare applications, and defense command centers. Market projections reflect this dominance as the global touchscreen industry is expected to grow by USD 17.3 billion between 2023 and 2028 [3]. With the evolving nature of immersive environments, VR and AR systems are increasingly seeking to replicate these interactions through virtual touchscreens and gesture-based input, which extends the use of an already familiar modality into three-dimensional (3D), embodied contexts.

One of the most comprehensive studies on gesture-based HMIs in VR was done by Schölkopf et al, who evaluated touchscreen automotive interfaces in VR as well as the surrounding knobs and buttons of the infotainment system and steering wheel dashboard [44]. Their findings demonstrated that the absence of haptic feedback severely reduced usability and user experience (UX) ratings, particularly for soft keys, rotary buttons, and touch gestures. The User Experience Questionnaire (UEQ) scores revealed a gap, leading the authors to conclude that VR-based UX assessment is “severely impaired” without haptic behavior being simulated [44]. The authors argued that meaningful UX studies in automotive VR could not be conducted without either passive haptic proxies, like physical mockups, or advanced haptic feedback gloves [44]. In their study, Schölkopf et al. also highlighted the magnitude of the problem when haptics is absent, as well as the practical implications of using VR in the early stages of prototyping in the automotive industry [44].

Beyond the individual experimental studies, review work has also underscored the importance of gesture-based interactions in immersive virtual environments. Shi and Shen provided a comprehensive survey of haptic feedback techniques and methods of tactile sensing in virtual environments, which highlighted that gesture recognition as one of the most direct and natural methods of interaction in VR applications [45]. The authors highlighted that gestures allow users to navigate and control tasks in ways that closely mirror real-world behavior, which makes them the main source of input in VR [45]. The authors further emphasized that without haptic feedback or a form of tactile sensing, the gestures are at risk of being incomplete, which reduces the ability of VR systems to convey realism and usability [45]. As summarized in table 4, Shi and Shen provided a comprehensive survey; their findings align with the findings from experimental work of reinforcing the functional power of gestures in VR, but remains constrained regarding which levels of haptic fidelity are sufficient for gestures.

Table 4- Prior Studies on Gestures & HMIs in VR

Study	Application	Factors Tested	Key Finding	Limitation
Schölkopf et al., 2021 [44]	Automotive VR Prototyping	Soft/ Hard Keys, Rotary Buttons, Touchscreen	Haptics absence reduced scores; Higher variability	Focused on Automotive; No haptic fidelity spectrum
Shi & Shen, 2024 [45]	Review of Haptic sensing and feedback techniques	General gesture recognition	Gestures are central input in VR; tactile sensing enhances realism	Review Based; no experimental validation

2.2 Haptic Fidelity in VR/AR Research

The effectiveness of haptic interaction in virtual environments depends on how close the haptic feedback devices can reproduce real-world interactions, this can be classified in terms of haptic fidelity by assessing which tactile and kinesthetic cues are reproduced (cf. Chapter1). The previous work has examined how variations in haptic realism affect user experience and task performance, typically within certain application domains or using a single specific device. Studies in this area have examined both low-fidelity techniques, such as vibrotactile techniques, and high-fidelity devices which usually contain multiple feedback modalities like force and tactile feedback.

2.2.1 Low Fidelity Haptics

Low fidelity haptic feedback devices often represent the sense of touch in symbolic ways. Such approaches are attractive because they are lightweight, low-cost, and portable, but they provide a simplified version of the cues rather than closely replicating the physical forces of real-world interactions.

As discussed previously, *VibroWeight* illustrates how synchronized vibrotactile and visual cues can enhance presence by simulating the perception of weight, without any kinesthetic resistance [6]. On the same foundation, more recent study explored the potential of finger-specific vibrotactile devices for object interactive contexts. Ravichandran and Nam showed that a vibrotactile device with localized vibrotactile actuators improved accuracy, task efficiency, immersion, and user satisfaction in virtual museum interactions compared to controller-based input [46]. Such results indicate that even abstract methods of representing the sense of touch can improve the effectiveness in manipulative and interactive tasks.

However, some performance trade-offs have been identified. Kourtesis et al. conducted a comparative study between vibrotactile and electrotactile feedback in VR-based Fitt's Law tasks and found that vibrotactile stimulation reduced both speed and accuracy relative to visual-only and electrotactile stimulation conditions [47]. This shows that while low fidelity devices can improve effectiveness in some applications like manipulative tasks, it also may reduce the effectiveness in other applications that require continuous control and rapid motor responses.

Taken together, the literature on low fidelity haptic feedback systems demonstrates that they can meaningfully enhance immersion, engagement, and task effectiveness with interactions that are primarily discrete in nature. As shown in Table 5, these approaches improve the subjective realism and user satisfaction, but their effectiveness vary depending on their application. The effectiveness is lower especially in tasks that require continuous actions or high precision. Given the advantages in terms of portability, bulkiness, and cost, the value of low fidelity haptic feedback devices can serve as accessible proxies for haptic feedback.

Table 5 - Prior Studies on Low-Fidelity Haptic Systems in VR

Study	Application	Factors Tested	Key Finding	Limitation
Wang et al., 2022 [6]	Weight Stimulation	Vibrotactile + visual cues	Enhanced realism, comfort, and presence compared to vibration-only or visual-only	No kinesthetic resistance; limited to weight perception
Ravichandran & Nam, 2024 [46]	Virtual museum object manipulation	Finger-specific vibrotactile glove	Improved accuracy, efficiency, immersion, and satisfaction vs. controller input	Focused on manipulative tasks; not tested with continuous gestures
Kourtesis et al., 2022 [47]	VR Fitts's Law pointing tasks	Vibrotactile vs. electrotactile vs. visual-only	Vibrotactile reduced speed and accuracy relative to electrotactile and visual-only	Limited for tasks requiring precision and rapid control

2.2.2 High Fidelity Haptics

High fidelity haptic devices aim to replicate the natural physical interactions with greater accuracy by combining tactile and kinesthetic feedback. Unlike low fidelity haptic devices, which approximate touch using symbolic cues, high fidelity systems render forces, object compliance, and surface properties closer to real life. Such systems allow the users to experience object resistance, object manipulation, and interact with virtual content in ways that resemble real-world dynamics more closely.

High haptic fidelity systems integrate multiple sensing and actuation modalities, including force-feedback exoskeletons, tactile actuators that use pneumatic or electric technologies to deliver localized contact and resistive forces. Pacchierotti et al. provide a comprehensive review of wearable fingertip and hand worn haptic devices [8]. Pacchierotti et al. describes these technologies as the closest approximation of 'true' haptic interaction in VR [8]. Their taxonomy highlights the ability of such devices to improve precision in manipulative tasks and increase realism, though often at the cost of added bulk, calibration needs, and reduced portability.

Empirical studies further show these trade-offs. Schölkopf et al. investigated automotive VR prototyping and indicated that the absence of realistic haptics reduced user ratings for touch-based input modalities, such as soft keys [44]. Their conclusion indicated that meaningful user Experience (UX) assessments in VR require the inclusion of haptic feedback, as visual-only conditions were insufficient for valid evaluation.

High fidelity gloves have also been evaluated in medical and training contexts. Boutin et al. reported that the neurosurgery residents that have been trained in VR with the use of haptic gloves achieved improved performance and expressed that the training is more realistic compared to visual-only counterparts [48].

A recent study that has been done on training in industrial contexts provides an additional case, Hornsby et al. investigated a VR glovebox simulation using the HaptX DK2 gloves [49]. The results show that while task completion time was slower in VR versus physical training, error rates, and recovery outcomes were comparable; Suggesting that high haptic fidelity gloves enable accurate and realistic interactions in industrial environments where replicating physical interactions are critical.

All in all, as summarized in table 6, the studies demonstrate that high haptic fidelity systems improve validity, task accuracy, and usability in VR contexts. However, their implementation is constrained by equipment bulk, complexity, and cost; such factors motivate the comparative investigation of fidelity levels under matched experimental conditions.

Table 6 - Prior Studies on High-Fidelity Haptic Systems in VR

Study	Application	Factors Tested	Key Finding	Limitation
Pacchierotti et al., 2017 [8]	Review of wearable fingertip and hand devices	Kinesthetic + tactile feedback capabilities	Classified gloves and exoskeletons as state-of-the-art for precision and realism	Review-based; limited experimental validation
Schölkopf et al., 2021 [44]	Automotive VR prototyping	Soft/ Hard Keys, Rotary Buttons, Touchscreen	Absence of haptic feedback reduced UX scores and increased variability	Focused on automotive; no direct device comparison
Boutin et al., 2024 [48]	Neurosurgical training	Haptic glove vs. visual-only	Improved performance metrics and reported realism over visual-only training	Limited to one surgical task and training cohort
Hornsby et al., 2025 [49]	Industrial glovebox training	Haptic gloves vs. physical baseline	Comparable error rates and realism to physical training; VR slower in task completion	Slower performance in VR; constrained to glovebox scenario

2.3 User Experience in Haptic VR

The influence of varying haptic fidelity on any virtual interaction cannot be understood without considering the impact on user-oriented outcomes. Prior research shows that variations in the levels of realism VR systems affect not only subjective measures of immersion and embodiment, but also objective measures like task performance. The measures used in prior research provide a good example on how to properly evaluate VR studies and in this case, how varying haptic fidelity levels affect the haptic user experience (HX) in VR.

2.3.1 Presence

As explained in the background, presence – *a dependent variable of this study* - is defined as the subjective psychological state in which users experience a sense of "being there" in a virtual environment. Presence is considered as one of the central constructs in VR evaluation because it captures the degree to which the virtual experience is acknowledged by the user as authentic and compelling. Unlike immersion, which refers to objective qualities of the system such as the VR headset resolution, the accuracy of the tracking system and algorithm, and sensory fidelity that an immersive system targets. Meanwhile presence, reflects the user's reaction or response to these system characteristics.

Psychology and medical field utilize presence as a concept of multidimensional state involving attentional focus, perceptual realism, and emotional involvement [50]. Research argues that presence is found in cognitive processes that allocate attentional and emotional resources to the mediated environment, effectively suspending awareness of the physical setting [50]. In clinical therapy context, presence influences treatment outcomes, like in treatment of phobias and in rehabilitation trainings [51]. Such applications explain that presence is not only metric used in measuring technological effectiveness, but also as a psychological measure to explain learning, behavioral transfer, and engagement in VR systems.

To evaluate presence, standardized self-report instruments are commonly used, with the *Igroup Presence Questionnaire (IPQ)* being one of the mostly adopted surveys. The IPQ divides presence into three subcomponents to be measured: spatial presence (the sense of being physically located in virtual space), involvement (the degree of attention devoted to the environment), and experienced realism (the perceived plausibility of the environment) [10]. IPQ has been consistently used due to its robustness and suitability for VR related human studies.

2.3.2 Embodiment

As introduced in the background, embodiment extends the concept of presence by measuring how users perceive their virtual body or as known as avatar. In the domain of the study, embodiment is categorized into three subcomponents: body ownership, agency, and change. The previously mentioned subcomponents help in explaining whether the user accepts the avatar as part of themselves, have a perception of control over actions, and feel spatially situated within it.

The concept of embodiment originates from psychology and neuroscience, where it is used in multisensory integration and body schema. when vision, proprioception, and tactile cues align, the brain would be able to attribute ownership to external objects, as demonstrated in the classic rubber hand illusion [39]. VR extends this phenomenon to full-body illusions, enabling applications in therapy, rehabilitation, and training [52]. For example, embodiment has been explored in phantom limb rehabilitation and post stroke motor recovery, with evidence suggesting that strong sense of embodiment leads to better motor recovery outcomes [53].

In terms of measurement, embodiment is often measured using self-reporting questionnaires that are built based on the body transfer literature. While studies adopt more classical measures like the body ownership by Longo et al. and the framework proposed by Gonzalez-Franco and Peck, there are recent instruments have been adapted specifically for interactive VR scenarios. The questionnaire presented by Roth and Latoschik extends the concept of measuring embodiment by incorporating items that explicitly target ownership, agency, and change under the conditions of VR [11]. Complementary approaches such as proprioceptive drift or physiological responses can provide evidence of embodiment, the use of questionnaires remain the predominant method due to their efficiency, practicality, and comparability across experiments. For these reasons, this study adopts the *Virtual Embodiment Questionnaire (VEQ)* as the instrument to evaluate embodiment.

2.3.3 System Usability

System usability is a critical factor in evaluating VR and haptic systems because it not only determines whether the user can complete the tasks assigned using the system, but also provides an insight on whether the technology is practical and acceptable for long-term use. When haptic fidelity increases, it often brings trade-offs, devices may become bulkier, more complex to calibrate, or require higher computational power, which can reduce the ease of use and overall satisfaction. Therefore, usability will serve as the balancing dimension, ensuring that any enhancements applied towards realism do not come at the cost of efficiency, effectiveness, or satisfaction. Within VR domains, usability has been widely used as the measure to determine the adoption of the proposed system, especially in training, rehabilitation, and industrial simulation, where the practicality of the system is just as important as its level of realism.

The most popular applied method of measuring usability is the *System Usability Scale (SUS),* a 10-item questionnaire developed by Brooke [12]. SUS provides a quick yet reliable measure of overall system effectiveness, efficiency, and user satisfaction, which makes it suitable for human studies in general and applied VR studies in specific. Usability scores in the VR domain often reveal challenges related to comfort and technical complexity regardless of the level of realism that the device delivers, which can provide insights correlated to the scores of perceived metrics like embodiment and presence.

Several studies have adopted the use of SUS or similar subjective usability instruments to evaluate the use of wearable or glove-based haptic systems. Moon et al.

compared three interaction conditions in a VR rhythm task: Controllers, hand tracking only, and vibrotactile gloves. They have administered the SUS questionnaire after the tutorial for each condition, with hand tracking being the highest (M = 86.6), then vibrotactile gloves (M = 83.82), then controllers (M = 76.04). Although the results showed no significant difference between the conditions, the usability results help to further explain their performance, engagement, and presence results.

CHAPTER THREE

Methodology

3.1 Research Design

This study adopts a 1×4 *between-subjects experimental design* for the evaluation of the impact of varying haptic fidelity levels on the perceived and functional validity of VR touchscreen interfaces. The participants are randomly assigned to one of the four experimental conditions:

- **High Haptic Fidelity Condition:** Tasks performed in VR with advanced tactile and force feedback actuators with enhanced hand tracking using the HaptX G1 gloves.
- **Low Haptic Fidelity Condition:** Tasks performed in VR with vibrotactile feedback using the bHaptics TactGlove DK2.
- **No Haptic Feedback Condition:** Tasks performed in VR with no tactile cues provided.
- **Real-World Control Condition:** Tasks performed on a physical touchscreen tablet, serving as the baseline for natural tactile interaction.

Table 7 provides a summary of the four experimental conditions.

Table 7 - Summary of the Groups/Conditions of the Study

Group 1	**Group 2**	**Group 3**	**Group 4**
VR Only with No Haptic Feedback	VR with Low Haptic Feedback	VR with High Haptic Feedback	Real Environment
			

This research design, consisting of the four groups allows for a systematic comparison across the spectrum of haptic fidelity, ranging from no haptic feedback at all to high multimodal haptic feedback.

The study tasks are derived from industry standards for the fundamental touchscreen gestures, which includes tap, pan, pinch, swipe, and rotate. A review of the top 100 mobile applications confirmed that tap, swipe, and pan were universally supported, pinch appeared in approximately 62% of apps, while rotate was far less common, supported in only 17%. Given this uneven representation and the practical limitations of implementing touchscreen rotation in VR environments, the rotate gesture was excluded from the study design (see Figure 15).

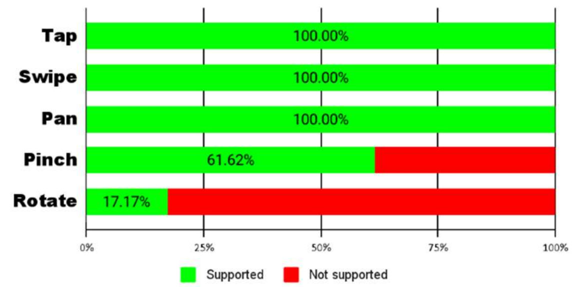

Figure 15-Supported gestures in top 100 mobile applications

Therefore, the final task set includes four tasks for the fundamental gestures, tap, pan, pinch, and swipe. Additionally, this study includes a fifth combinational task which combines the four previously mentioned fundamental gesture into a compound interaction. The task set that this study provides ensures ecological validity on the gestures that are most widely used in touchscreen interfaces while also maintaining the feasibility of the experiment performed.

For analytical clarity, the gestures have been categorized into two groups, Discrete gestures (Tap, and Swipe) and continuous gestures (pan and pinch). The combinational task is treated separately as a combinational task, as it integrates the fundamental touchscreen gestures into a more complex, real-world like scenario. This categorization enables us to investigate the impact of haptic fidelity on simple versus complex gestures interactions, as well as addressing Research Question 3 (RQ3) regarding the sensitivity of haptic fidelity.

The dependent variables include subjective and objective measures. The subjective measures include presence, embodiment, and system usability which are captured through Igroup Presence Questionnaire (IPQ), the Virtual Embodiment Questionnaire (VEQ), and the System Usability Scale (SUS) respectively. Objective measures include performance metrics, which are defined as accuracy, error rate, task completion time, and gesture speed, which are derived from the real time logging system implemented on the tasks. The capture of both experiential and performance-based outcomes shows that this study provides a mixed methods approach.

A between-subjects design was selected rather a within-subjects approach to minimize unwanted effects like carry-over, fatigue, and learning effects, which are particularly problematic in studies that use VR and virtual environments as the users rapidly adapt to new sensory cues. Additionally, random assignment to the four groups ensures balanced participant distribution and helps mitigate any demographic or experiential biases. To further reduce unwanted learning effects, all participants start with a tutorial phase consisting of one practice trial per task before starting the experimental trials. The main study then proceeds with a uniquely randomized order for the tasks for each participant, ensuring that the same sequence of tasks is not repeated across individuals. Each of the four fundamental gestures and the combinational task is repeated three times, resulting in a total of fifteen trials per participant, with ordering randomized on the individual and group level.

This research design, that combines systematic haptic fidelity variation with validated subjective questionnaires and objective performance metrics, directly addresses the central research question of *"How varying haptic fidelity levels affect the perceived and functional validity of touchscreen interactions in VR?"*. Additionally, the inclusion of both VR conditions and real-world benchmark condition not only enables the comparisons across the different levels of haptic fidelity but also compares the functional validity of the simulated interactions against natural tactile interaction.

3.2 Participants

An a priori power analysis was conducted on the G*Power 3.1 Software to determine the minimum required sample size for this study. The analysis was set for a fixed-effects one-way ANOVA (omnibus F-test) with the number of groups set to four, corresponding to the four haptic fidelity conditions. The other parameters were specified as a medium effect size of $f = 0.30$, an alpha level of $\alpha = 0.05$, and the desired statistical power of 0.80. The calculation results showed a required total sample size of 128 participants, with 32 participants per group. As shown in figure 16 and figure 17, the analysis showed a critical F-Value of 2.6777, with numerator degrees of freedom (df_{num}) = 3 and denominator degrees of freedom (df_{den}) = 124. The noncentrality parameter was calculated as $\lambda = 11.52$, which yields an actual achieved power of 0.81, slightly exceeding the desired threshold. This sample size calculation ensures that the study has sufficient sensitivity to detect meaningful effects of haptic fidelity on the perceived and performance metrics.

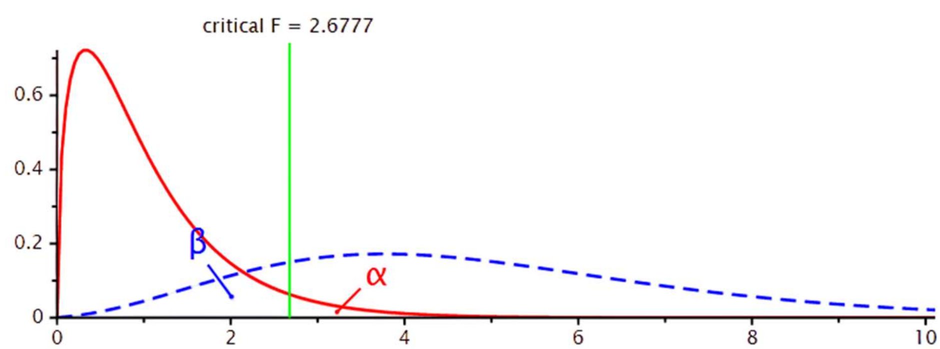

*Figure 16 - Power Analysis Plot Generated by G*Power*

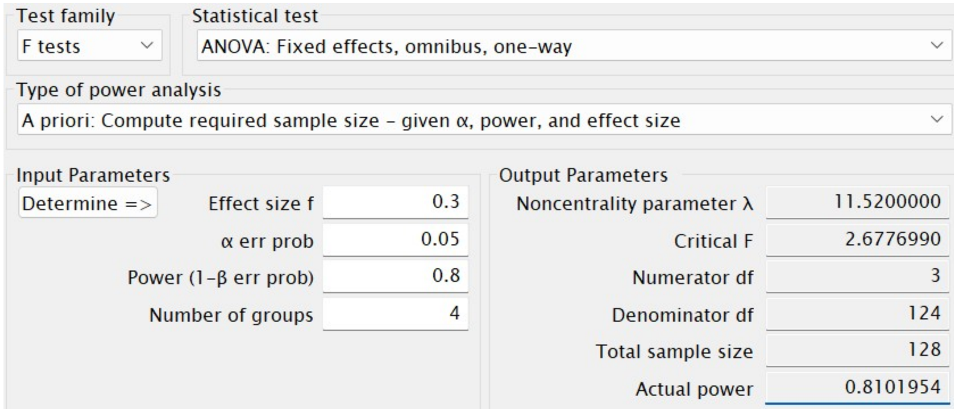

*Figure 17 - G*Power output for a priori power analysis*

This study was approved by the Oakland University Institutional Review Board (IRB-FY2025-56) under expedited review, with initial approval granted on October 24,2024 and modifications approved on November 7,2024 to mitigate additional risks (VR sickness and skin irritation) and updated compensation methods (see Appendix A). All of the methods and procedures are conducted in accordance with federal regulations and ethical principles of the Belmont Report.

Participants are recruited through the Oakland University's student body and the surrounding community using IRB-approved materials, including flyers, email announcements, and recruitment messages. Additional promotion was conducted via the network of the faculty, laboratory announcements, and social media channels associated with the research team.

The inclusion criteria of the participants required them to be between 18 and 64 years old and fluent in English. Exclusion criteria were implemented for the participant safety and data integrity. Individuals were excluded if they have any of the following:

- Require corrective glasses incompatible with the VR headset.
- Any arm, hand, or motor limitations restricting touchscreen interaction.

- History of epilepsy, seizures, migraines, or severe motion sickness.
- Reported susceptibility to VR-induced discomfort.
- Contagious skin, scalp, or hair conditions.
- Pregnant.
- Difficulty sitting for extended periods with the headset.

In terms of ethical safeguards, prior to the participation, individuals reviewed and signed the IRB approved informed consent form, which outlines the study purpose, procedures, risks, and compensation structure. Additionally, to ensure the safety of participants, the study requires the participants to fill out the Virtual Reality Sickness Questionnaire (VRSQ) both after the tutorial phase and the main study phase.

Participants filled out a demographic survey prior to the study, capturing age, gender, VR and haptic gloves familiarity, handedness, and hand size. This information supports the conduction of post hoc analyses for potential demographic effects on VR performance.

The data collected through this study is anonymized using randomly generated participant ID codes, securely stored on encrypted institutional servers, and accessible only to the research team. No personally identifying information was linked to the performance or questionnaire data.

At the time of the writing, ninety participants had completed the study out of the planned 128. This milestone represents more than 70% of the total planned sample size, providing substantial dataset for preliminary analyses while full recruitment and testing continued. The demographic survey revealed that the participants are primarily in their twenties and early thirties, with the majority being males. The majority also reported limited prior experience interacting with a VR headset and very little exposure to VR gloves, while the hand preference was predominantly right-handed.

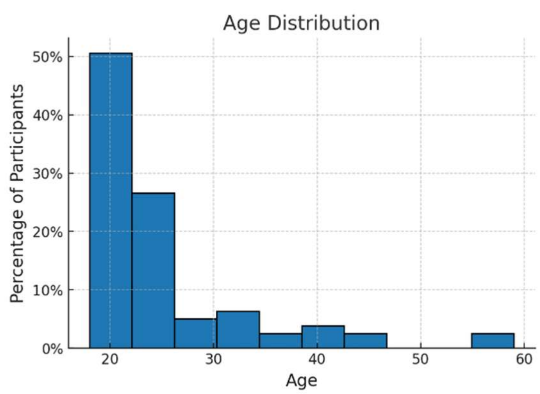

Figure 18 - Age Distribution of Participants

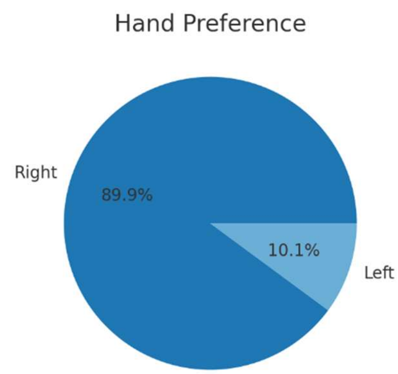

Figure 19 - Hand Preference of Participants

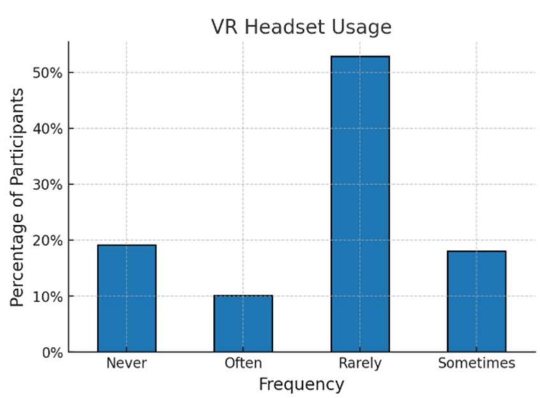

Figure 21 - VR Headset Usage of Participants

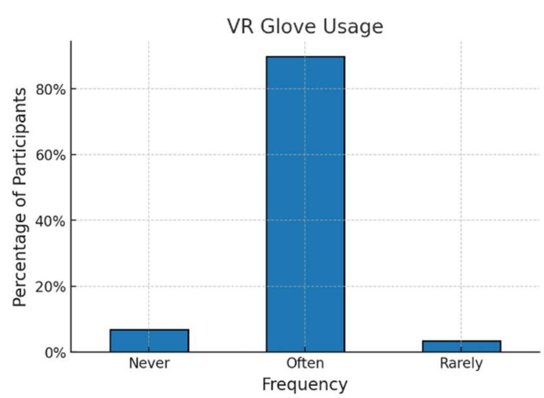

Figure 20 - VR Glove Usage of Participants

3.3 Apparatus and Materials

The apparatus for this study includes virtual reality hardware, haptic feedback gloves, and custom software tools and environments that were developed to support the experimental nature of the study. All of the studies were conducted in a controlled laboratory at Oakland University, ensuring the consistency of conditions across experimental sessions.

The participants assigned for the three VR conditions interacted with a head-mounted display (HMD) that rendered the experimental environment. The virtual environment included a table top, tablet touchscreen interface, the background environment, and the virtual hands; Which allowed the users to perform gesture-based interactions similar to those on a physical device. The HMD used in the experiment is the Varjo XR-3 mixed reality headset, which provides industry grade resolution (70 pixels per degree), wide field of view, integrated eye-tracking, and precise 6DoF positional tracking.

This study utilized two wearable haptic feedback gloves to represent the two different haptic fidelity levels. For the low haptic fidelity group, the participants wore the bHaptics TactGlove Dk2 gloves, which provided vibrotactile feedback through six vibration actuators per glove distributed across the fingertips and the wrist. Meanwhile for high haptic fidelity group, the participants wore the HaptX G1 gloves, each glove provides advanced tactile and kinesthetic feedback using 135 microfluidic tactile actuators distributed across the fingertips and the palm area and 5 force feedback actuators on each finger of the glove. The no haptic feedback group involved only hand-tracking without any haptic device, the participants were asked to wear white disposable fabric gloves in all VR conditions for sanitary reasons. Meanwhile the real-world group utilized a Microsoft Surface Pro 4 tablet for the interaction with a physical touchscreen.

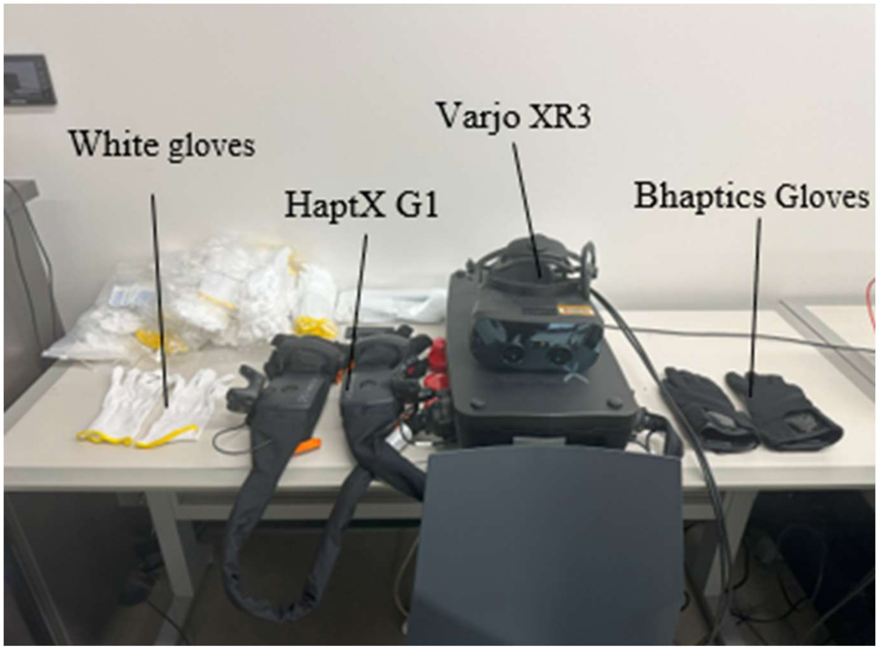

Figure 22 - Hardware Used for The Three VR Conditions

Figure 23 - Tablet Touchscreen Used for Real-World Condition

The virtual experimental environment was developed on Unreal Engine 4.27, with a custom user interface that presented tasks to participants. The project included touchscreen gesture recognition, task randomization, and performance logging. The tasks were hosted on a server that the touchscreen interface displayed, the tasks support session based, event based, and time-based logging, capturing metrics such as gesture type, gesture direction, accuracy, error rates, and times. The logged data is stored as JSON format on the server, which is being sent to a proxy server then parsed and stored on Google Sheets for further analysis.

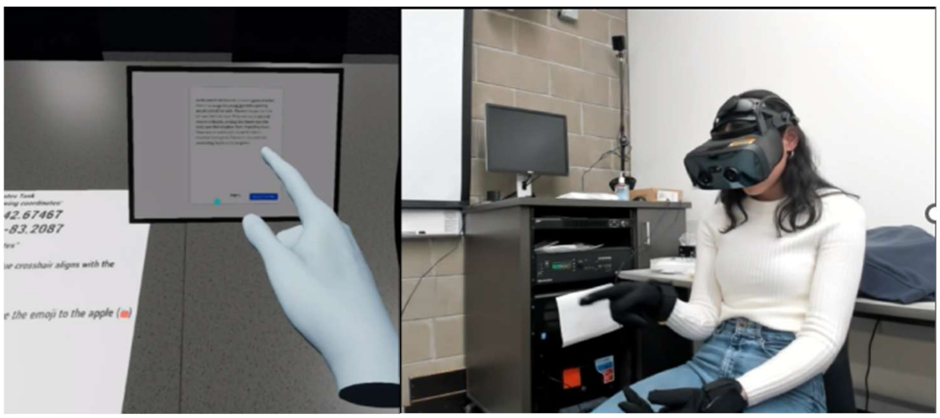

Figure 24 - VR Environment

The participants completed several surveys and questionnaires as part of the apparatus:

- **Demographic Survey (see Appendix C):** Age, gender, VR and Haptic familiarity, preferred hand, and hand size.
- **Virtual Reality Sickness Questionnaire (VRSQ) (see Appendix C):** Administered after the tutorial phase and after the full experiment to monitor cyber sickness of the user.
- **Presence (IPQ), Embodiment (VEQ), and Usability (SUS) (see Appendix C):** Measured after the task completion for measurement and analysis.

3.4 Experimental Tasks

The tasks employed in this study are derived from the fundamental touchscreen gestures previously discussed, which have been chosen to reflect the common interactions in modern user interfaces while varying in motor complexity. These tasks included tap, swipe, pan, and pinch, in addition to a combinational task that integrates all four gestures into a sequential workflow.

The tap task was designed to have the user to quickly and accurately tap on the box that spawns randomly in shape, color and position on the screen. This task represents a discrete, low-complexity gesture that is universally supported in touchscreen applications (see Figures 25, 26).

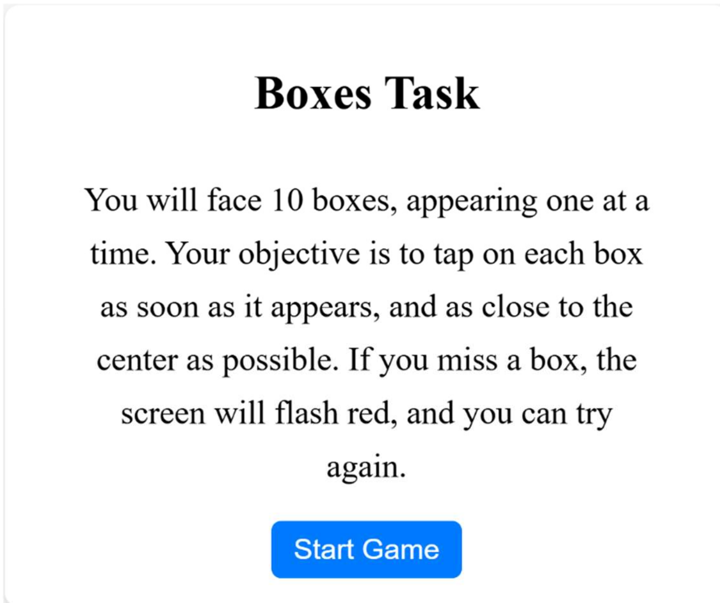

Figure 25 - Tap Task Start Screen

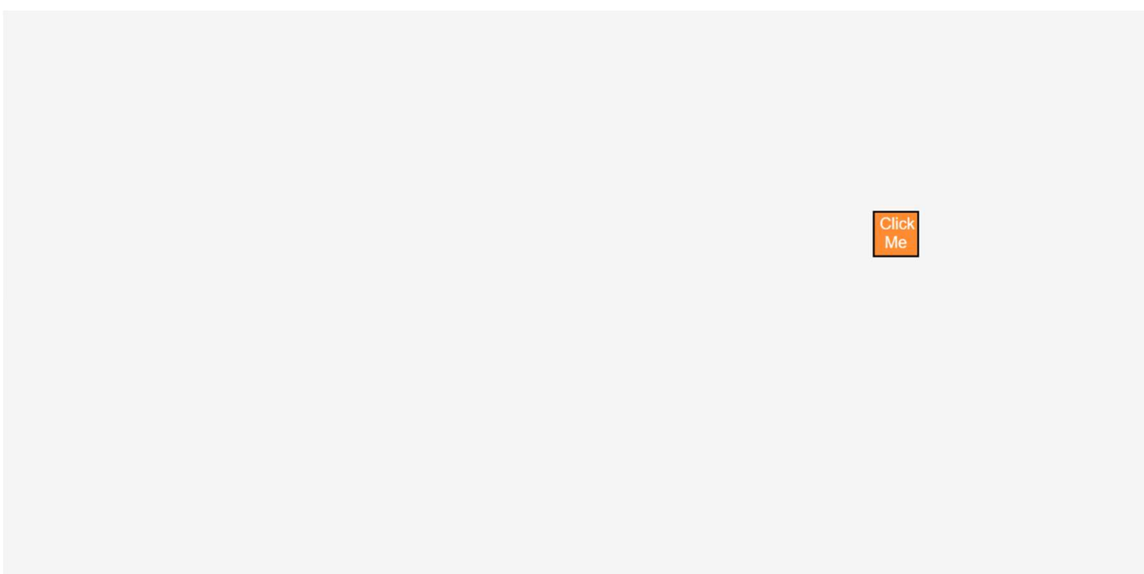

Figure 26 - Tap Task: Randomly Spawned Box

The swipe task required participants to swipe across the touchscreen to navigate to a randomly chosen page out of twenty pages. Similar to tap, swipe is a discrete gesture but requires more spatial coordination (see Figures 26, 27).

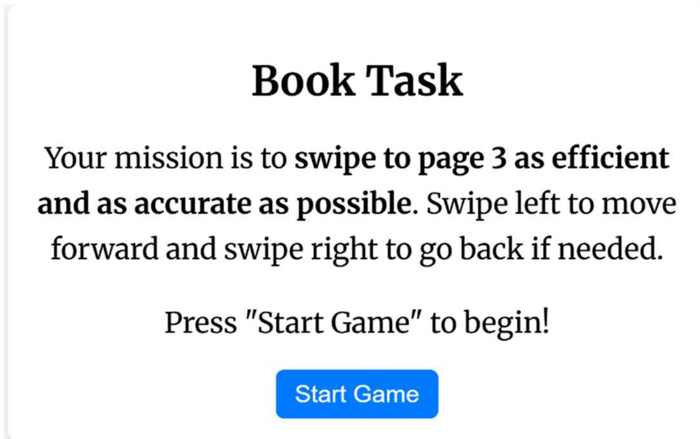

Figure 27 - Swipe Task Start Screen

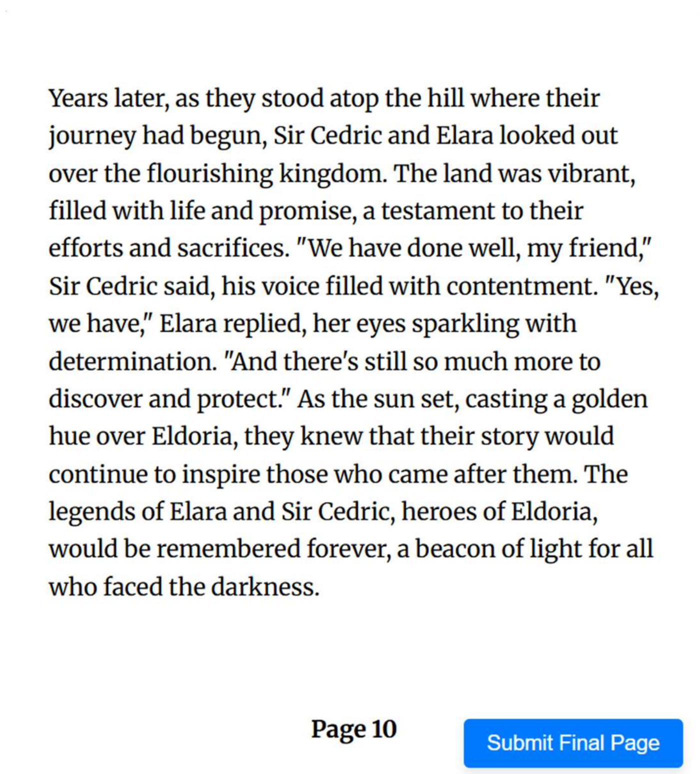

Figure 28 – Swipe Task: Page 10 of the E-book

The pan task included three sliders, horizontal, vertical, and diagonal. The participants were asked to slide the slider's knob to a desired randomly generated percentage, one at a time. Unlike tap and swipe, pan is a continuous gesture, which demands sustained finger to surface contact and precise motion control (see Figure 29-32).

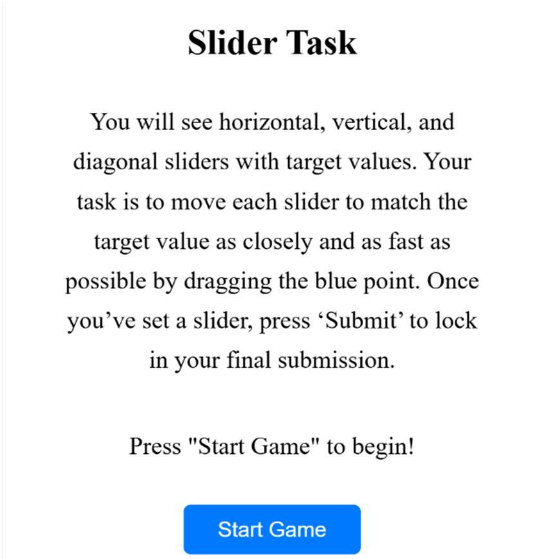

Figure 30 - Pan Task Start Screen

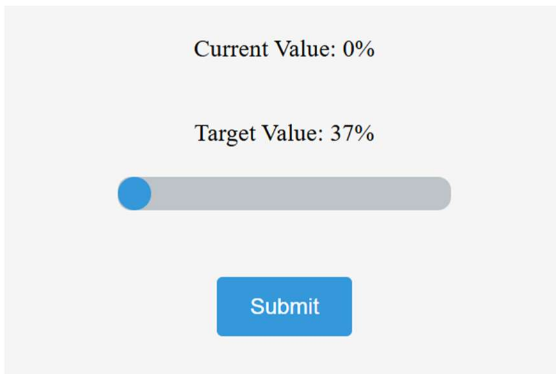

Figure 29 - Pan Task Horizontal Slider

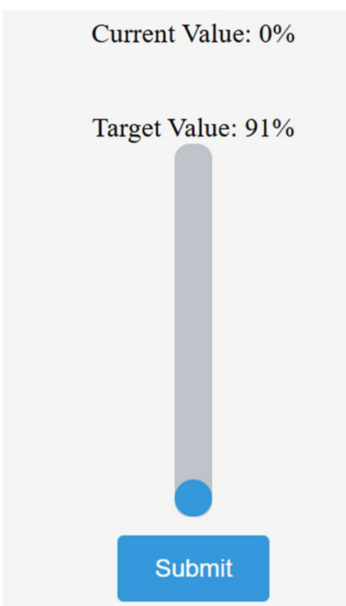

Figure 31 - Pan Task Vertical Slider

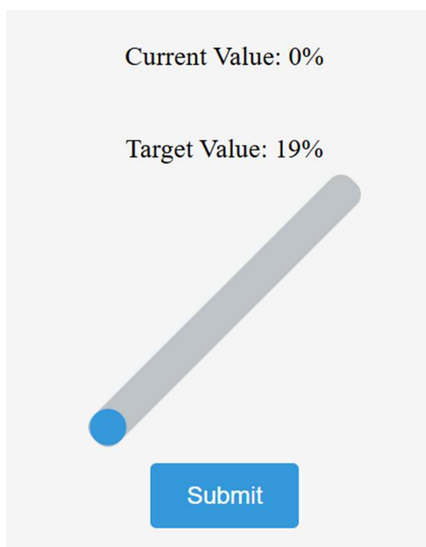

Figure 32 - Pan Task Diagonal Slider

The pinch task instructs participants to resize a star to meet the size of the dashed border line by zooming using a two-finger pinch gesture. Pinch requires fine motor control, coordination, and scaling precision, which makes it highly sensitive to differences in haptic fidelity (see Figures 33, 34).

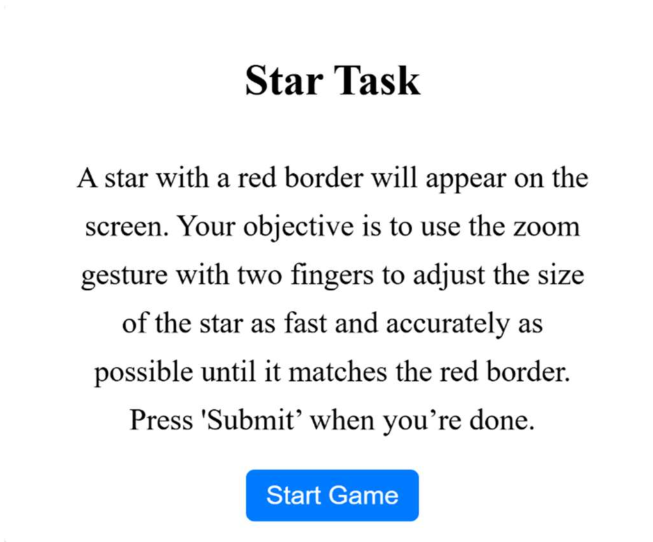

Figure 33 - Pinch Task Start Screen

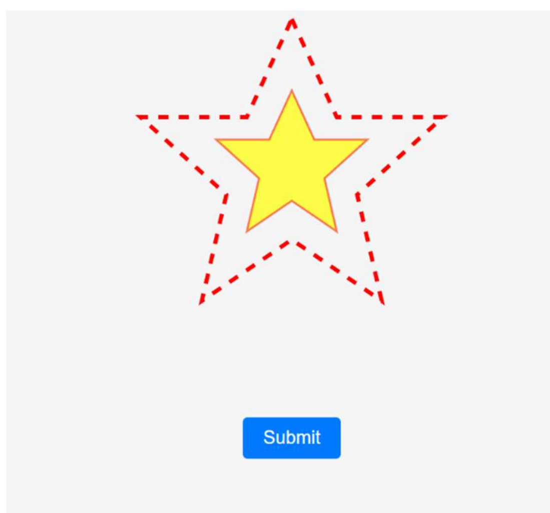

Figure 34 - Pinch Task: Yellow Star & Red Borderline

The map task has been designed to integrate all four of the previously mentioned fundamental touchscreen gestures. Participants were first instructed to enter a provided longitude and latitude by typing on a numeric keypad, then they were instructed to locate the coordinates and align the blue crosshair box with the white cut-out on the map in terms of size and position. Afterwards, the users were asked to swipe the blue crosshair box to navigate between the different emojis until they have reached the apple emoji (see Figure 35-38).

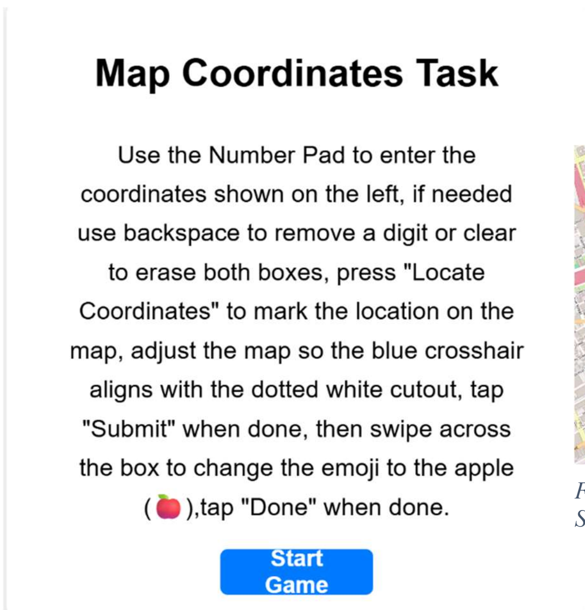

Figure 35 - Combinational Task Start Screen

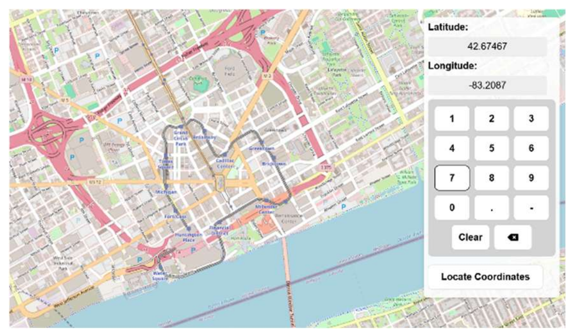

Figure 36 - Combinational Task: Coordinate Typing Screen

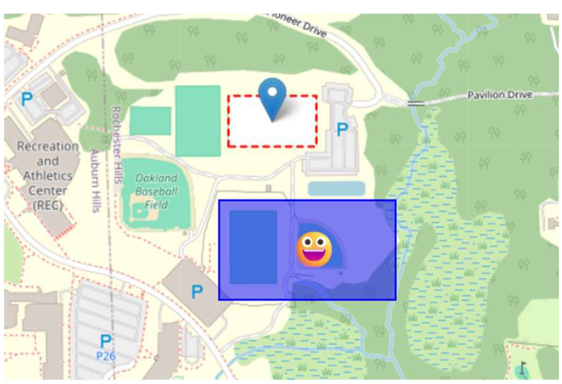

Figure 37 - Combinational Task: Resize & Replace Blue Crosshair Screen

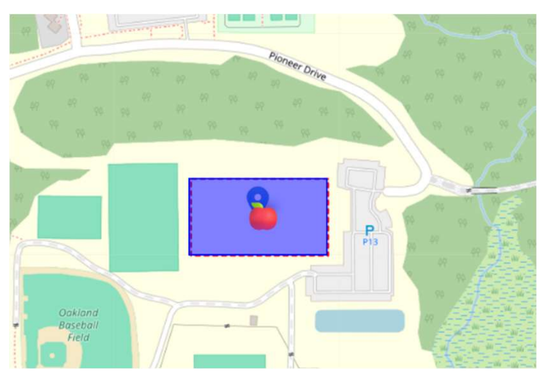

Figure 38 - Combinational Task: Emoji Selection Screen

3.5 Procedure

This study is designed to provide a smooth and consistent experience while minimizing biases, learning effects, fatigue, and potential VR discomfort. Each experimental session follows the same sequence, lasting approximately 60 minutes per participant.

Upon the arrival, participants are greeted and briefed on the study goals and procedures. Afterwards, they are handed over the consent form and given the opportunity to go through it as well as asking any questions before signing. Participants then completed the demographic survey to capture their background variables such as age, gender, VR and haptics familiarity, preferred hand, and their hand size for glove fitting if applicable.

Before beginning the tasks, participants are informed more about the devices as well as a video walking through the tasks. Those assigned to VR conditions were seated and fitted with the HMD, and where applicable, the corresponding haptic gloves. During the tutorial phase, participants complete one practice trial of each task to become familiar with the equipment and interaction style of the touchscreen and tasks. This step also does ensure the learning effects are reduced during the main experiment. A Virtual Sickness Questionnaire is administered following the tutorial phase to assess their initial tolerance.

Participants are then proceeded to the main study session, which included 15 tasks that are random in order and each task was repeated three times. The randomization is unique for each participant, ensuring no two participants experienced the same sequence.

During this phase, objective performance metrics are logged in real time. After the completing the tasks, participants filled out the Virtual Reality Sickness Questionnaire to ensure they remain in good health to proceed to the next steps of the experiment. Afterwards, participants remain seated after the completion of the main set of tasks to complete the presence, embodiment and system usability questionnaires.

At the end of the session, participants were debriefed on the study's purpose and given the opportunity to provide feedback about their experience. Compensation was provided as a $15 gift card, with a $10 bonus gift card given to the top 10% performers after the full analysis is complete.

CHAPTER FOUR

Results

4.1 Assumption Checks and Data Preparation

All preprocessing, statistical testing, and visualization were performed in *Python 3.10* using the libraries *pandas, numpy, scipy.stats, statsmodels, and matplotlib*. Statistical significance was evaluated at $\alpha = 0.05$. For each analysis, the test statistic and corresponding p-value were reported. Event- and session-based logs were merged into participant-level datasets, and tutorial runs were excluded a priori. For each gesture task (Tap, Swipe, Pan, Pinch) and the combinational Map task, the three valid trials per participant were averaged to produce a single value per outcome. Trials flagged as aborted, timed-out, or corrupted were excluded prior to analysis.

Subjective measures were scored according to their published specifications. Presence was calculated as both a total score and by its subcomponents (Spatial Presence, Involvement, and Experienced Realism). Likewise, embodiment was computed as a total score and by its subcomponents (Ownership, Agency, and Change). System Usability was computed as a total score after standard reverse coding on designated questionnaire items and scaling to a 0–100 range. Participants with incomplete surveys were excluded from those analyses, and no imputation was performed.

Assumptions were evaluated for every dependent variable (subjective and objective) within each group. Normality was tested using the Shapiro–Wilk test and visually inspected via Q–Q plots and histograms. Homogeneity of variances was assessed using Levene's test. Because human performance data often exhibit right-skew and questionnaire responses may show ceiling effects, several outcomes deviated from normality and/or variance homogeneity. Accordingly, a one-way ANOVA with Tukey HSD post hoc tests was used when assumptions were met, while a Kruskal–Wallis H test with Bonferroni-adjusted Dunn post hoc comparisons was applied when normality was violated. No data transformations (e.g., log or Box–Cox) were applied. Independence was ensured through the between-subjects design and random assignment of participants.

The outliers of the study's outcomes were inspected via boxplots; none were removed because no cases were identified as measurement or logging artifacts. Descriptive summaries are reported as $means \pm standard\ deviations\ (SD)$.

4.2 Subjective Measures

This section presents the results of the subjective measures that were collected following each participant's interactions with the experimental setup. The subjective measures in this study capture the perceived experience across multiple psychological constructs that complement the objective performance data. The subjective instruments include Presence, Embodiment, and System Usability questionnaires, each scored according to their published specifications as outlined in chapter 3. The three measures assess how convincingly the virtual interaction was experienced, the degree to which participants identified with their virtual body and actions, and their perceived usability of the system as a whole. The following subsections present the analysis results for each measure, beginning with Presence.

4.2.1 Presence

Presence indicates whether participants feel a sense of "being there" and how immersed they are in the virtual environment. It also captures the subjective realism and spatial awareness elicited by the system. In this study, Presence was analyzed as a *total score* and through its three subcomponents: *Spatial Presence, Involvement,* and *Experienced Realism*. Each subcomponent provides a focused perspective on how haptic fidelity influenced the participants' perceptual and cognitive engagement with the virtual task.

Presence - Total Score:

The assumption checks for the total Presence score showed near-normal distribution characteristics based on the Shapiro–Wilk test, Q–Q plots, and visual inspection of histograms. Levene's test indicated acceptable homogeneity of variances across groups. Therefore, a one-way ANOVA was used to evaluate group effects.

The analysis revealed no statistically significant differences in overall Presence between the High, Low, and No Haptic Fidelity groups ($p > 0.05$), indicating that the general feeling of "being there" was largely unaffected by the addition or quality of haptic feedback. This suggests that, within the tested range of haptic fidelity, participants' sense of presence was driven primarily by the visual and interactive consistency of the environment rather than the haptic feedback aspect.

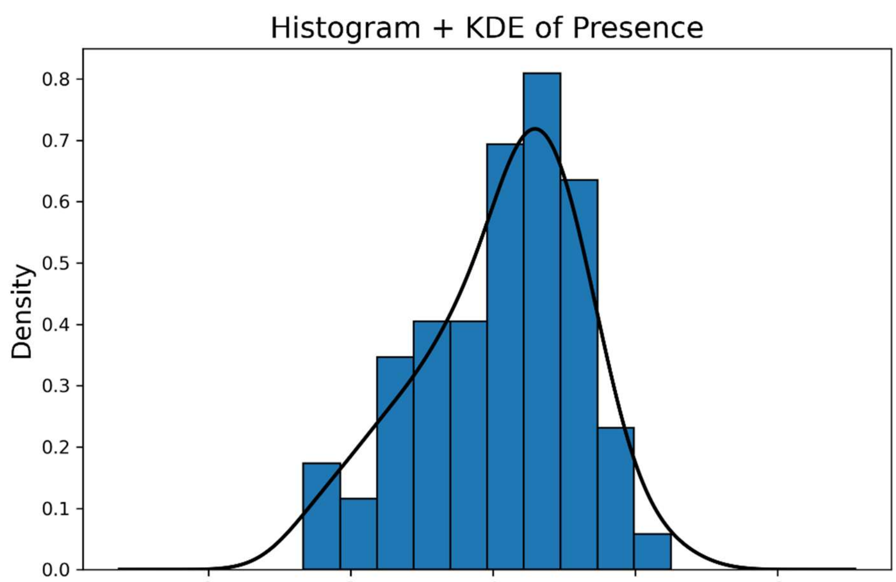

Figure 39 – Histogram + KDE of Presence

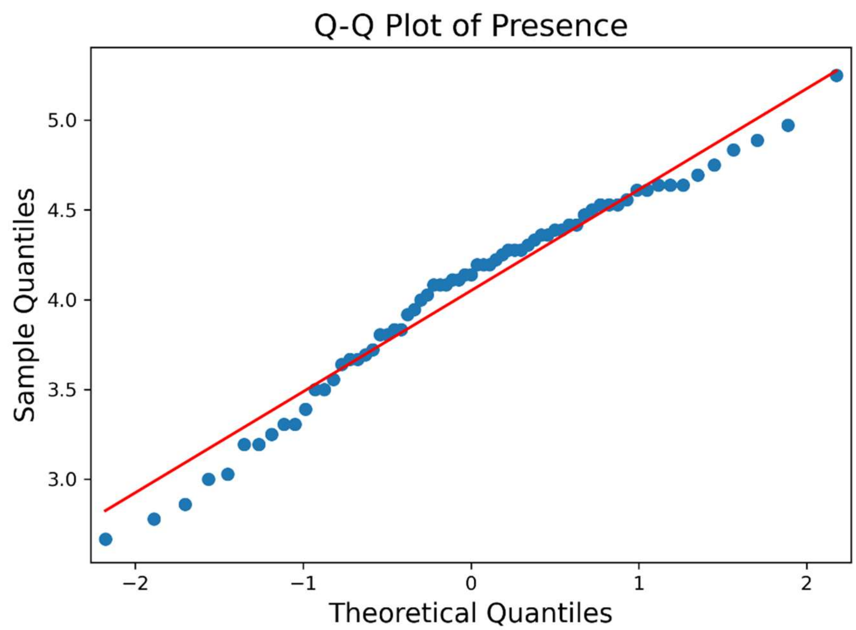

Figure 40 - Q-Q Plot of Presence

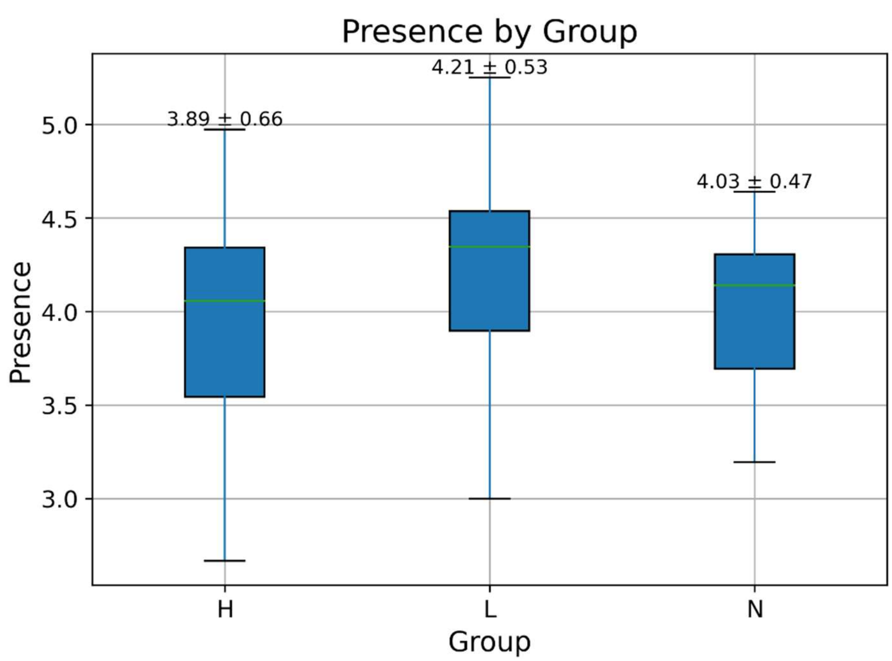

Figure 41 - Presence Box Plot

Table 8 - Presence ANOVA Table

Source	SS (Sum of Squares)	df	MS (Mean Square)	F-Value	p-Value	ω² (Effect Size)
Between Groups	1.178	2	0.588870	1.883	0.1604	0.026
Within Groups	20.013	64	0.312703	—	—	—
Total	21.191	66	—	—	—	—

Spatial Presence:

The assumption checks for Spatial Presence showed deviations from normality based on the Shapiro–Wilk test, Q–Q plots, and visual inspection of histograms. Given these violations, the non-parametric Kruskal–Wallis H test was used to evaluate group differences across the High, Low, and No Haptic Fidelity conditions. The analysis revealed no statistically significant differences ($p > 0.05$).

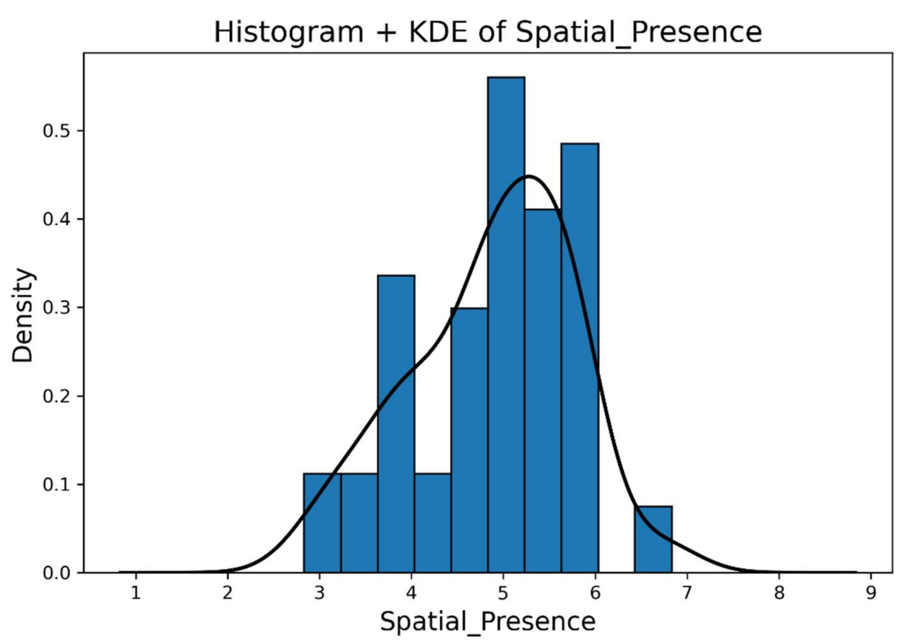

Figure 42 - Histogram + KDE of Spatial Presence

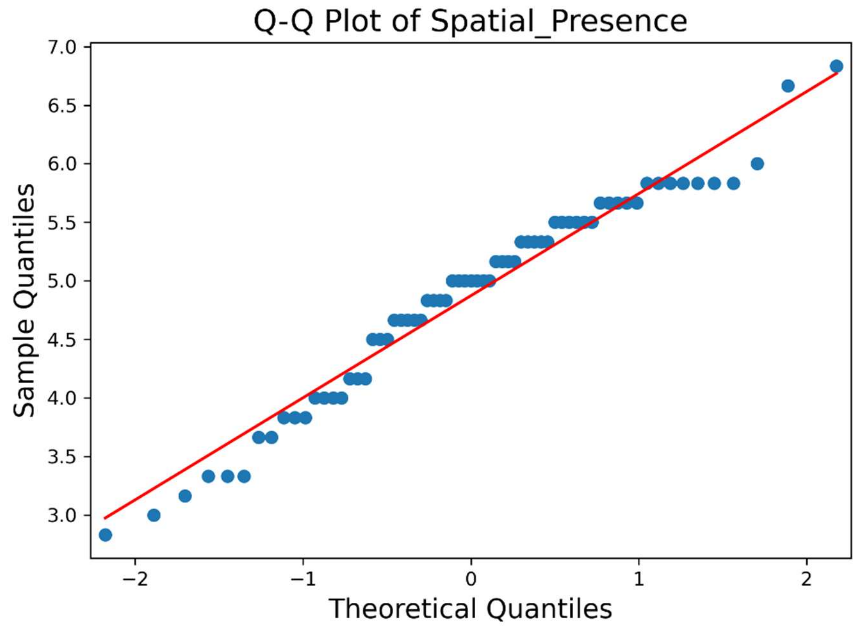

Figure 43 - Q-Q Plot of Spatial Presence

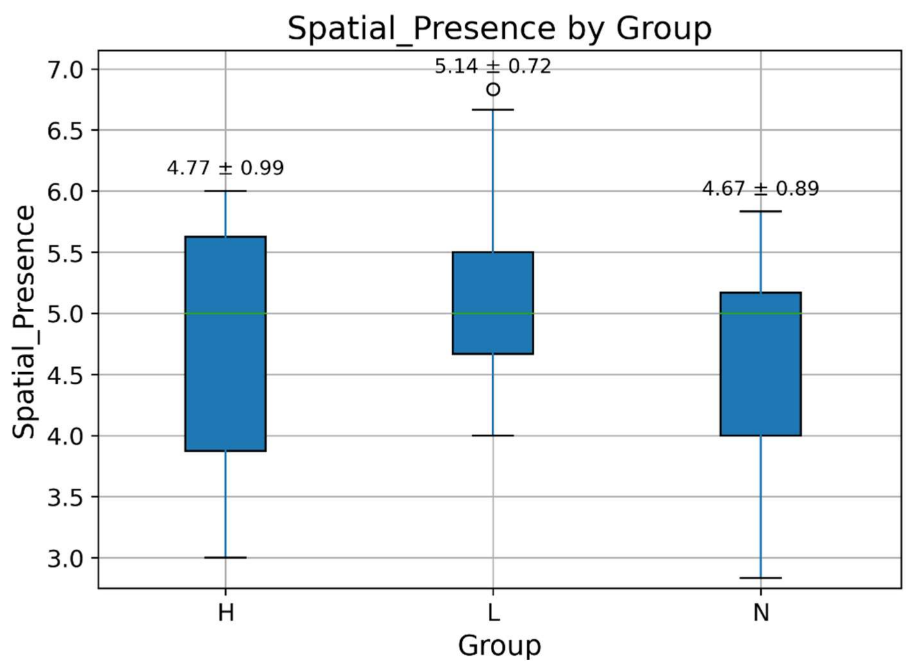

Figure 44 - Spatial Presence Box Plot

Involvement:

The assumption checks for Involvement showed near-normal distribution characteristics based on the Shapiro–Wilk test, Q–Q plots, and visual inspection of histograms. Levene's test indicated acceptable homogeneity of variances across groups. Therefore, a one-way ANOVA was used to evaluate group effects. The analysis revealed no statistically significant differences ($p > 0.05$).

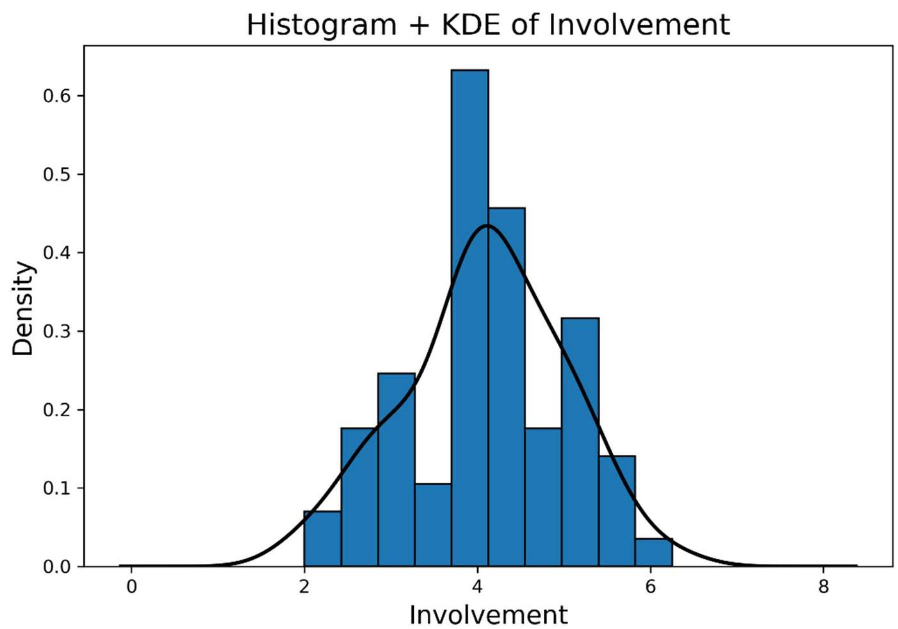

Figure 45 - Histogram + KDE of Involvement

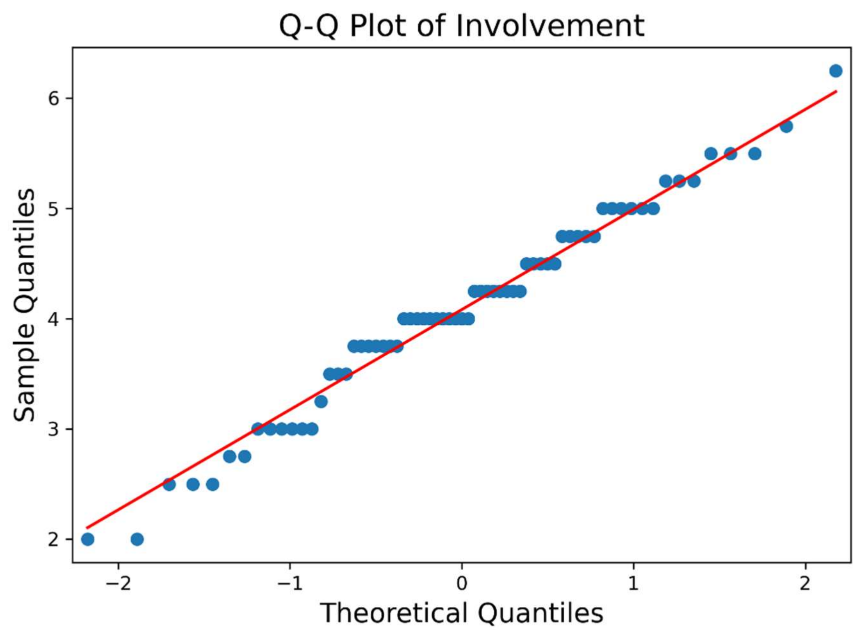

Figure 46 - Q-Q Plot of Involvement

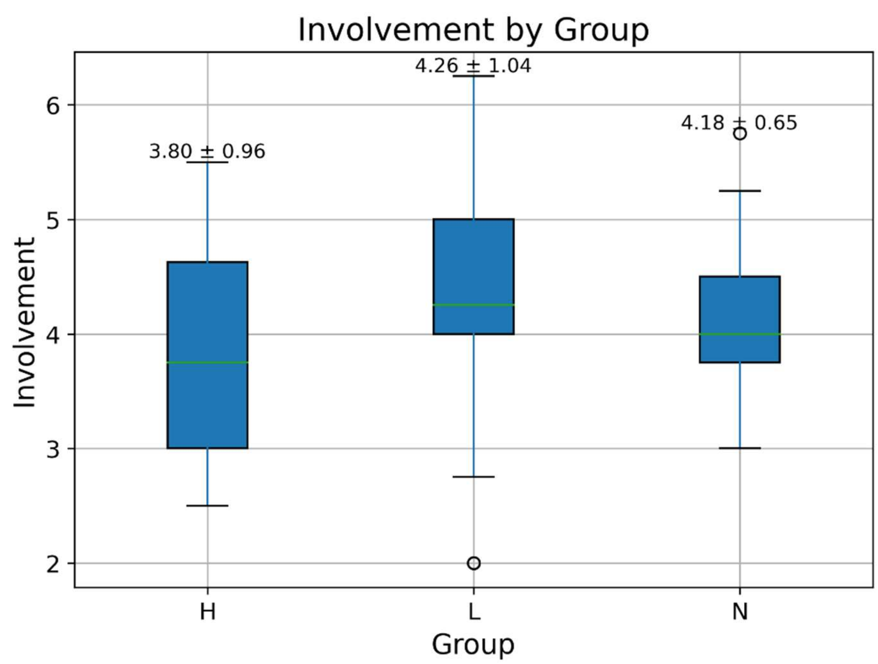

Figure 47 - Involvement Box Plot

Table 9 - Involvement ANOVA Table

Source	SS (Sum of Squares)	df	MS (Mean Square)	F-Value	p-Value	ω^2 (Effect Size)
Between Groups	2.766	2	1.383105	0.1685	0.1936	0.020
Within Groups	52.532	64	0.820817	—	—	—
Total	55.298	66	—	—	—	—

Experienced Realism:

The assumption checks for Experienced Realism showed deviations from normality based on the Shapiro–Wilk test, Q–Q plots, and visual inspection of histograms. Given these violations, the non-parametric Kruskal–Wallis H test was used to evaluate group differences across the High, Low, and No Haptic Fidelity conditions. The analysis revealed no statistically significant differences ($p > 0.05$).

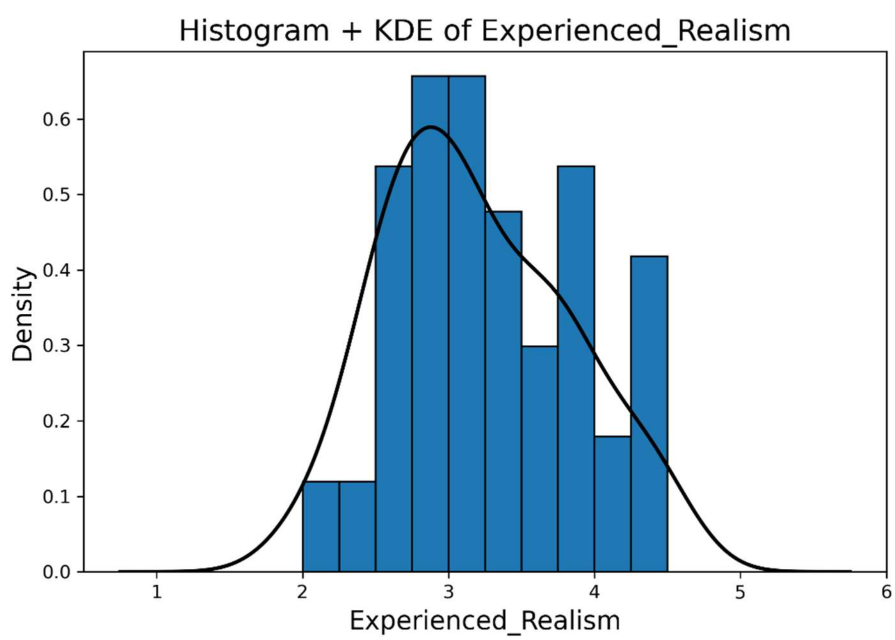

Figure 48 - Histogram + KDE of Experienced Realism

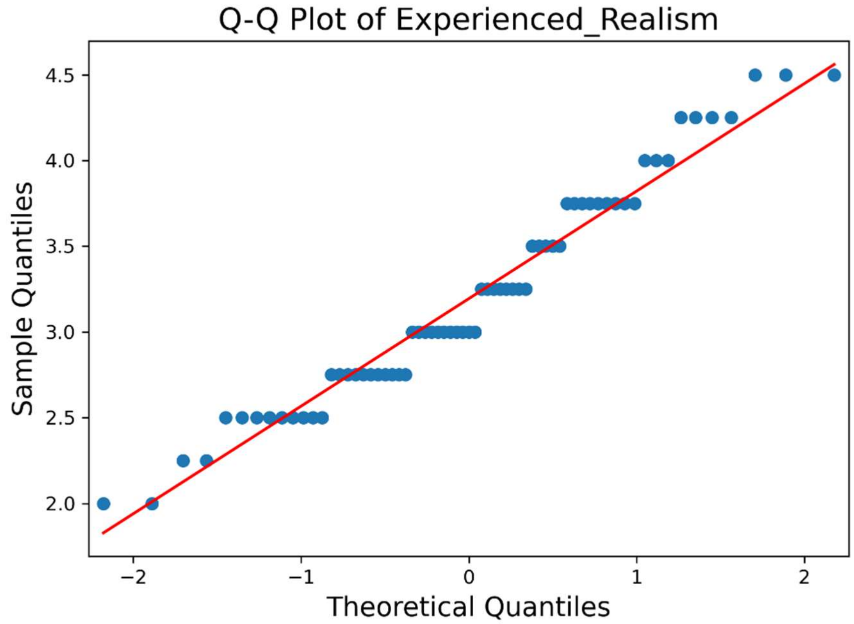

Figure 49 - Q-Q Plot of Experienced Realism

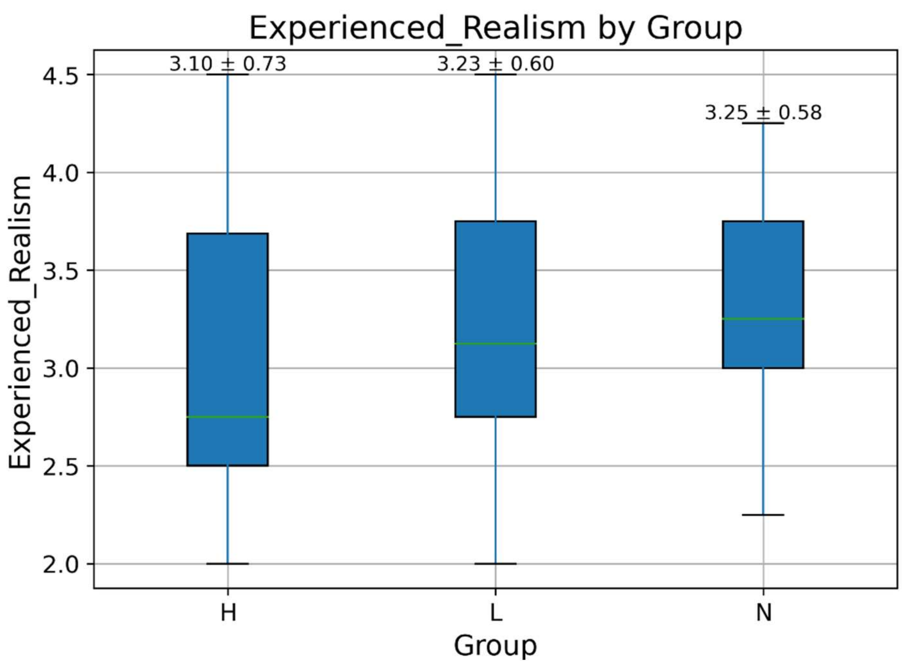

Figure 50 - Experienced Realism Box Plot

4.2.2 Embodiment

Embodiment is a reflection of the degree to which participants experience a sense of ownership, control, and identification with their virtual representation. It captures how effectively the system conveys body ownership, agency, and change within a virtual world. In this study, Embodiment was analyzed both as a *total score* and through its three subcomponents: *Ownership, Agency, and Transformation*. Each subcomponent provides a focused view of how haptic fidelity influenced participants' perceived connection to their virtual body.

Embodiment - Total Score:

The assumption checks for the total Embodiment score showed near-normal distribution characteristics based on the Shapiro–Wilk test, Q–Q plots, and visual inspection of histograms. Levene's test indicated acceptable homogeneity of variances across groups. Therefore, a one-way ANOVA was used to evaluate group effects.

The analysis revealed no statistically significant differences in overall Embodiment between the three groups ($p > 0.05$), suggesting that haptic fidelity did not strongly influence participants' perceived integration of the virtual body or sense of control. This suggests that, within the tested range of haptic fidelity, participants' sense of embodiment was driven primarily by the visual and interactive consistency of the environment rather than the haptic feedback aspect.

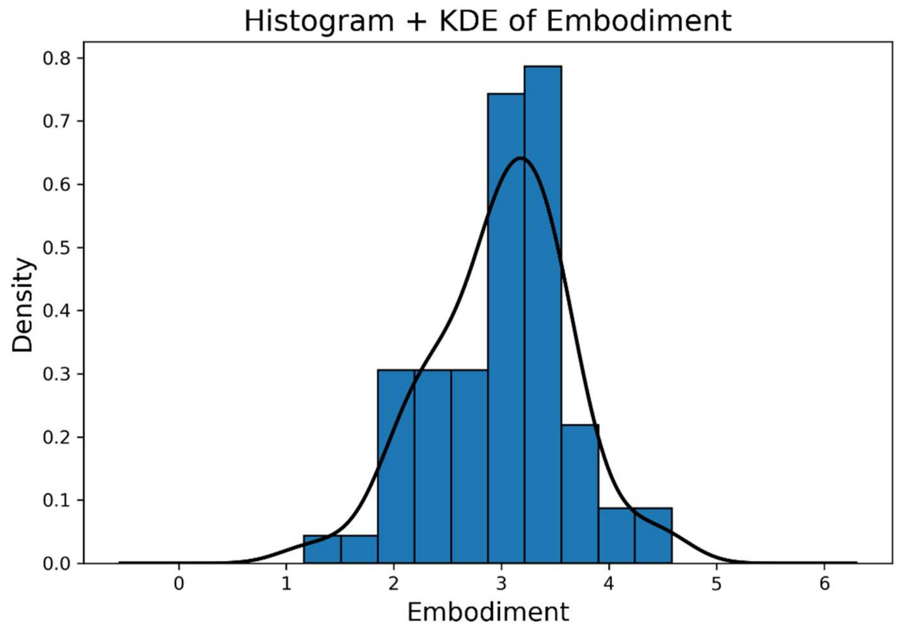

Figure 51 - Histogram + KDE of Embodiment

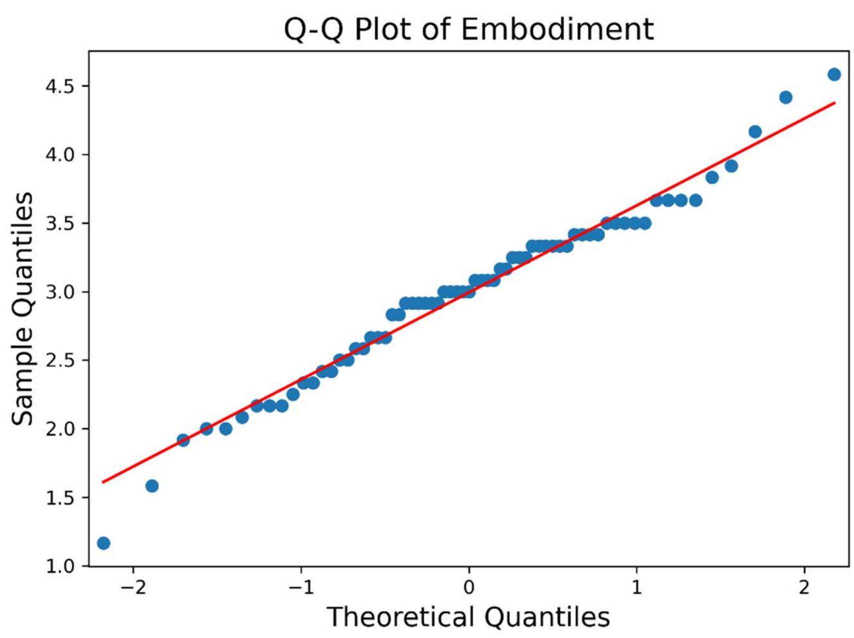

Figure 52 - Q-Q Plot of Embodiment

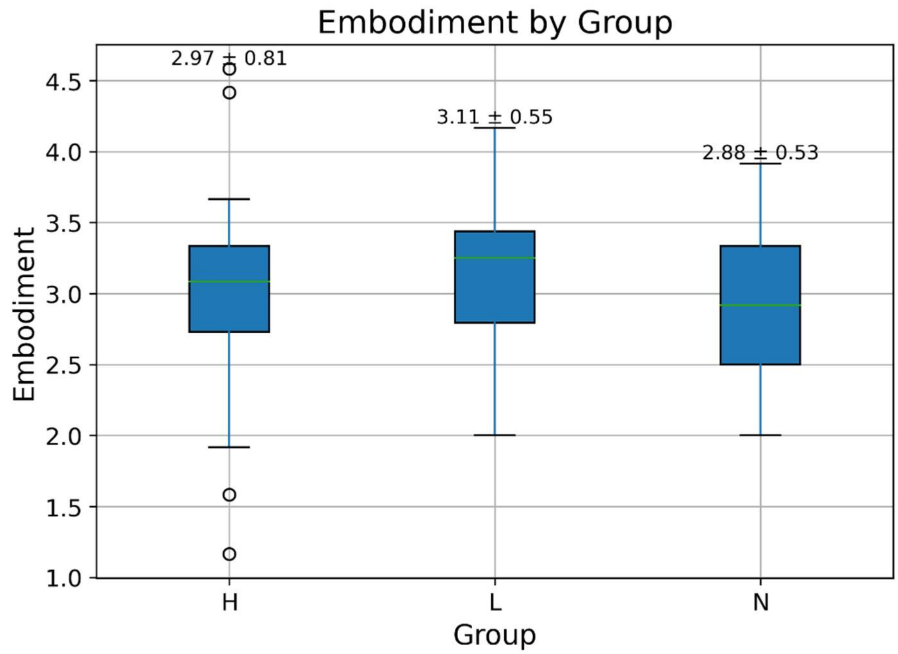

Figure 53 - Embodiment Box Plot

Table 10 - Embodiment ANOVA Table

Source	SS (Sum of Squares)	df	MS (Mean Square)	F-Value	p-Value	ω² (Effect Size)
Between Groups	0.587	2	0.294	0.713	0.494	-0.009
Within Groups	26.353	64	0.412	—	—	—
Total	26.940	66	—	—	—	—

Ownership:

The assumption checks for Ownership showed deviations from normality based on the Shapiro–Wilk test, Q–Q plots, and visual inspection of histograms. Given these violations, the non-parametric Kruskal–Wallis H test was used to evaluate group differences across the High, Low, and No Haptic Fidelity conditions. The analysis revealed no statistically significant differences ($p > 0.05$).

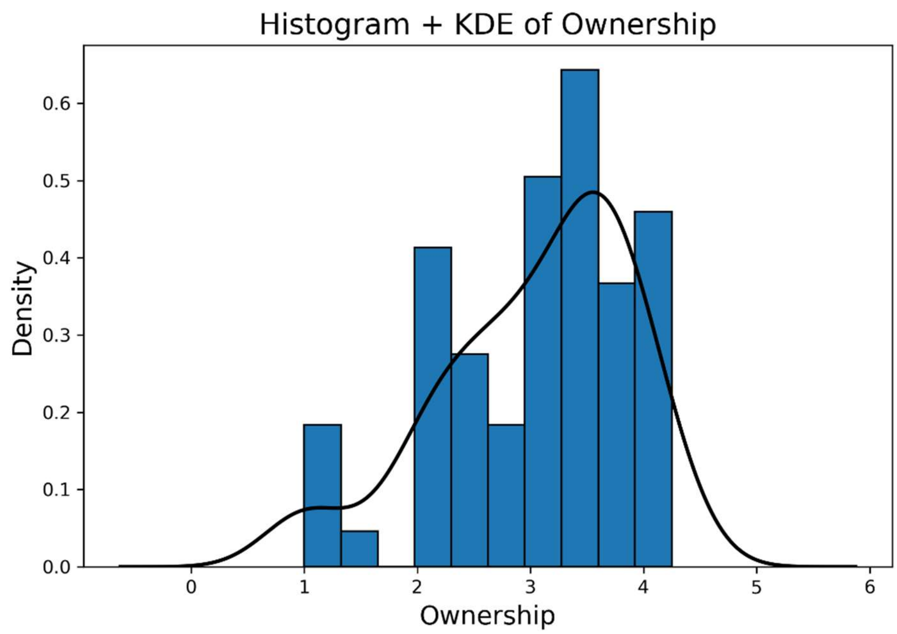

Figure 54 - Histogram + KDE of Ownership

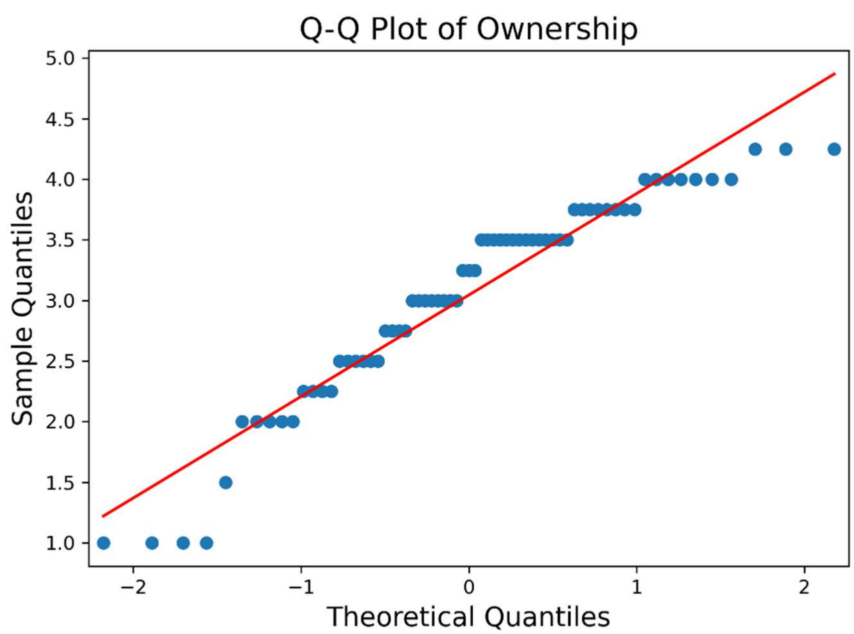

Figure 55 - Q-Q Plot of Ownership

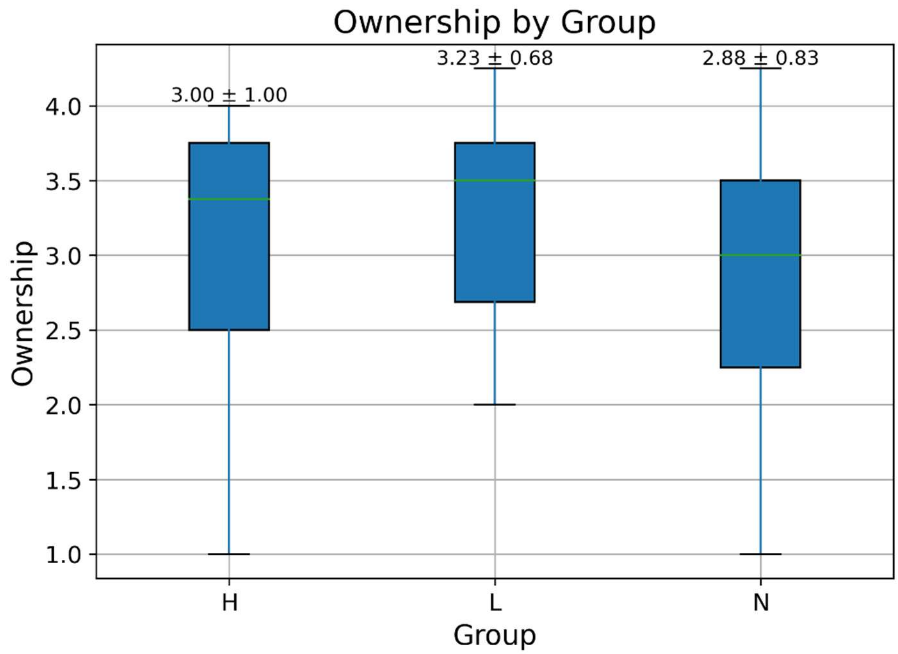

Figure 56 - Ownership Box Plot

Agency:

The assumption checks for Agency showed deviations from normality based on the Shapiro–Wilk test, Q–Q plots, and visual inspection of histograms. Given these violations, the non-parametric Kruskal–Wallis H test was used to evaluate group differences across the High, Low, and No Haptic Fidelity conditions. The analysis revealed no statistically significant differences ($p > 0.05$).

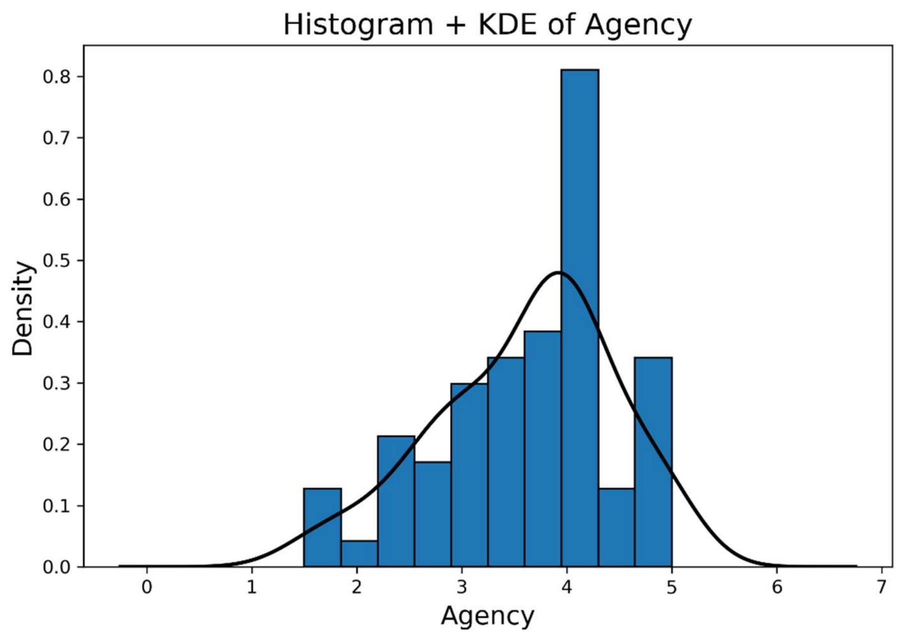

Figure 57 - Histogram + KDE of Agency

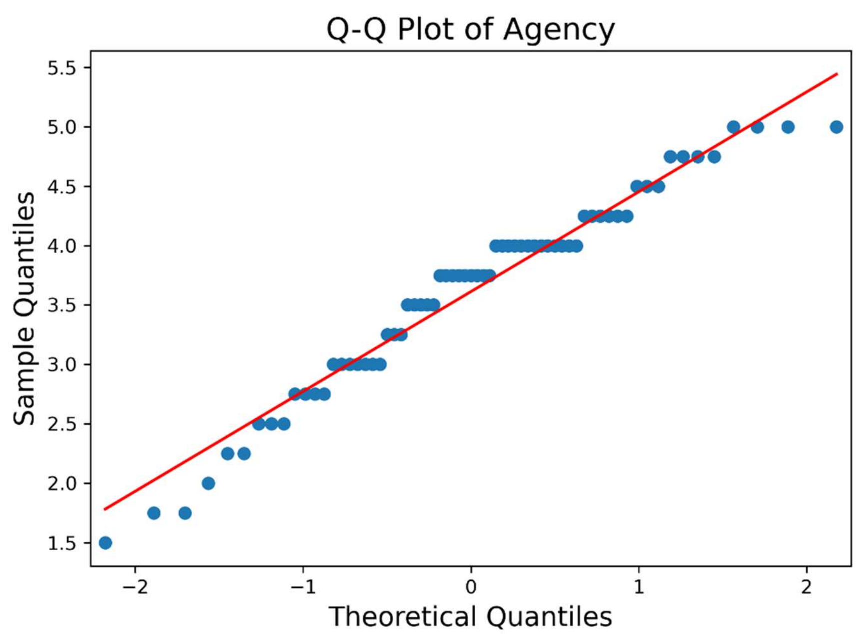

Figure 58 - Q-Q Plot of Agency

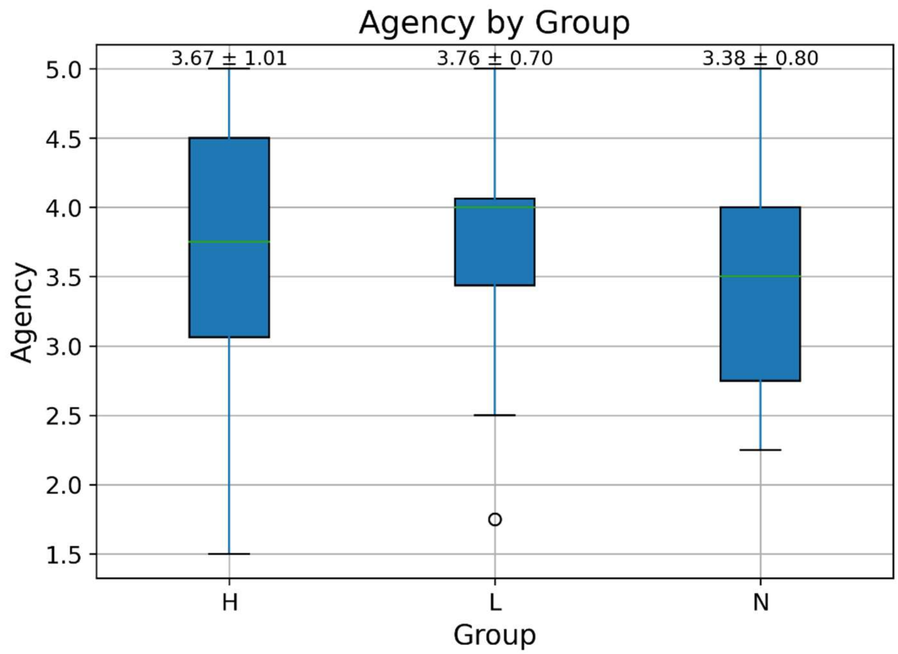

Figure 59 - Agency Box Plot

Change:

The assumption checks for Change showed deviations from normality based on the Shapiro–Wilk test, Q–Q plots, and visual inspection of histograms. Given these violations, the non-parametric Kruskal–Wallis H test was used to evaluate group differences across the High, Low, and No Haptic Fidelity conditions. The analysis revealed no statistically significant differences ($p > 0.05$).

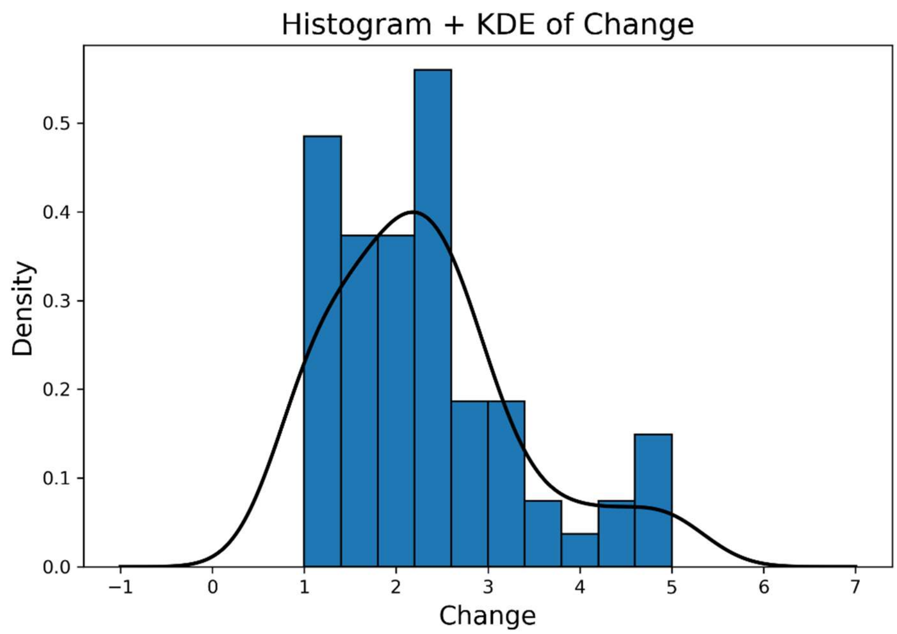

Figure 60 - Histogram + KDE of Change

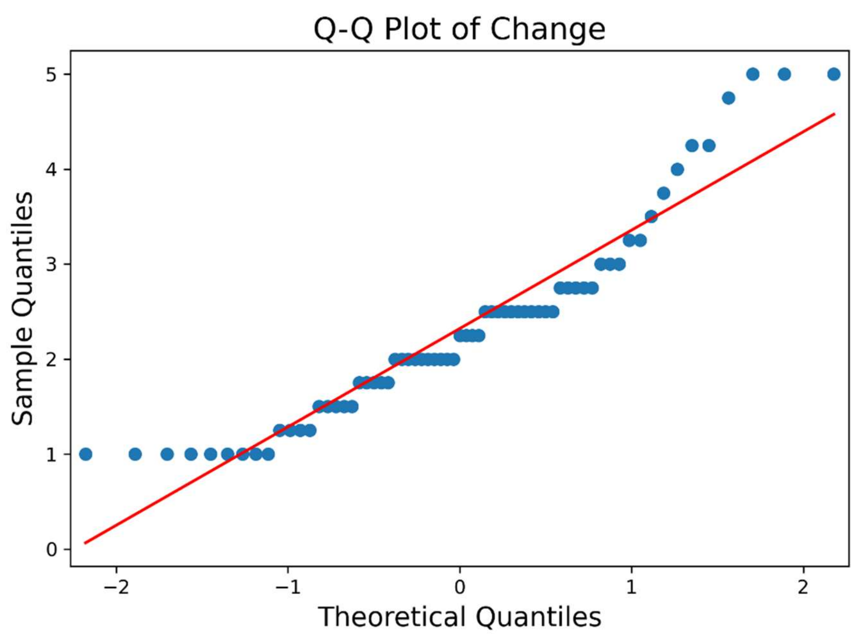

Figure 61 - Q-Q Plot of Change

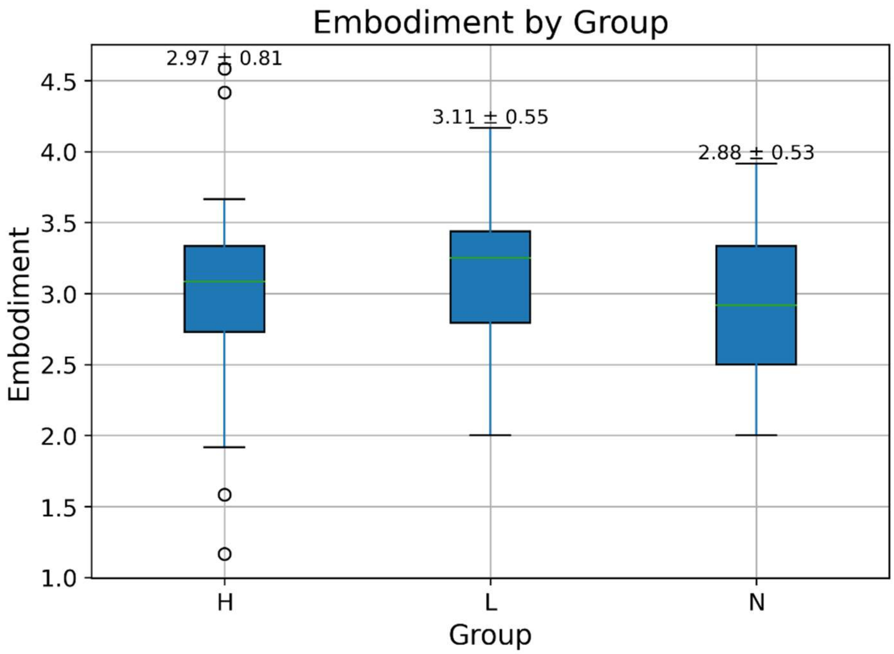

Figure 62 - Change Box Plot

4.2.3 System Usability

System usability reflects how intuitive, efficient, and satisfying the interaction with a system is from a user's perspective. Additionally, system usability represents the extent to which users are able to complete their tasks with minimal effort and frustration. In this study, system usability was measured using the System Usability Scale (SUS), a standardized 10-item questionnaire. The SUS total score is normalized to a 0-100 scale and computed by reverse-coding even-numbered items and scoring odd numbered items as is with a subtraction of one from their score.

The assumption checks indicated that SUS scores were approximately normally distributed, as supported by the Shapiro–Wilk test, histogram, and Q–Q plots. Levene's test confirmed homogeneity of variances across groups. Therefore, a one-way ANOVA was conducted to examine the effect of haptic fidelity on perceived system usability.

The ANOVA results indicated no statistically significant difference in usability scores among the High, Low, and No Haptic Fidelity groups ($p > 0.05$), suggesting that the presence or fidelity of tactile feedback did not substantially influence how participants perceived the system's usability. The means, however, followed a descriptive pattern: the low haptic fidelity group exhibited the highest average SUS score, followed by the high and no haptic fidelity conditions. According to the standard SUS interpretation, all three systems achieved mean scores above 60, indicating that they are generally considered usable and meet the threshold for acceptable user experience, though none reached the "excellent usability" range (above 80).

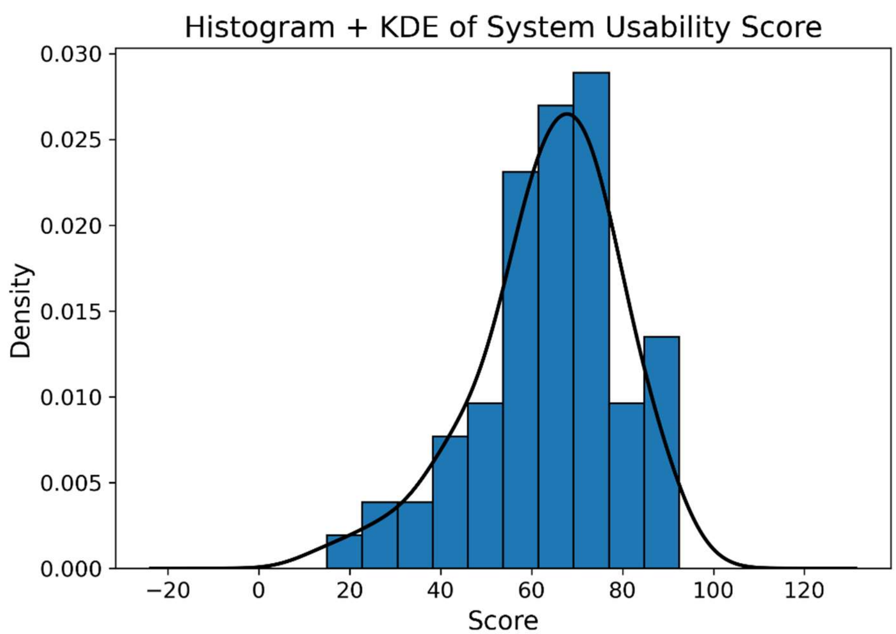

Figure 63 - Histogram + KDE of System Usability

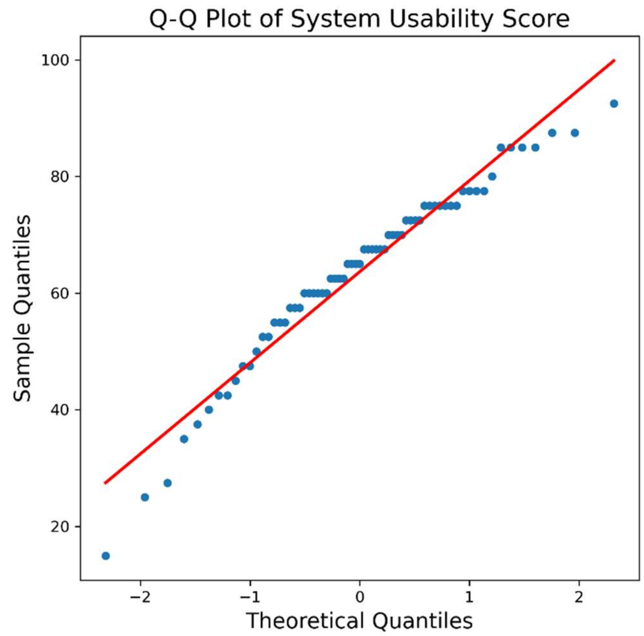

Figure 64 - Q-Q Plot of System Usability

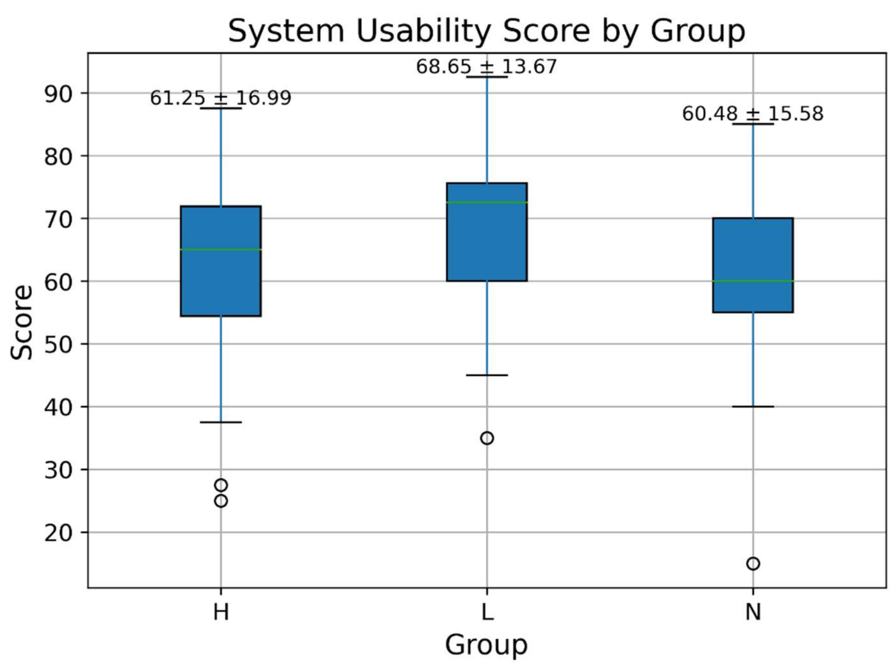

Figure 65 - System Usability Box Plot

Table 11 - System Usability ANOVA Table

Source	SS (Sum of Squares)	df	MS (Mean Square)	F-Value	p-Value	ω^2 (Effect Size)
Between Groups	937.25	2	468.63	1.97	0.148	0.028
Within Groups	15216.85	64	237.76	—	—	—
Total	16154.10	66	—	—	—	—

4.3 Objective Performance Measures

The objective performance measures are analyzed to quantify the participants' actual interaction performance across the five tasks: Tap, Pan, Pinch, Swipe, and the combinational Map Task. The performance measures are complementary to the subjective ratings discussed in the previous section, capturing how efficiently and accurately participants completed the tasks and executed each gesture under different haptic fidelity conditions. For each task, key performance metrics were extracted and averaged across the three valid trials per participant per task. The key performance metrics extracted are: *Accuracy, Error rate, Task Completion Time,* and *Speed*. The aim of the performance measures analysis is to determine whether varying levels of haptic fidelity (High, Low, None) produced measurable differences in users' performance, and whether any haptic fidelity condition approaches real-life task performance. Assumption checks (normality and homogeneity of variances) were conducted for each dependent variable to guide the appropriate use of one-way ANOVA or Kruskal–Wallis tests. The following subsections present the results for each gesture task individually, including relevant figures, statistical outcomes, and interpretations.

4.3.1 Tap Task

The tap task is designed to evaluate the participants' abilities to select target locations on a touch screen using the tap gesture. The task represents a discrete gesture where success depends on spatial accuracy rather than continuous haptic feedback. Thus, this task provides insight into whether tactile cues influence fundamental point-based interactions in virtual environments.

Accuracy:

The assumption checks for the tap task accuracy did not support normality within groups, but Levene's test showed heterogeneity of variances ($F(3,86) = 13.57$, $p < 0.001$), primarily driven by the real-world group's zero variance (ceiling at 1.00). Thus, the Kruskal-Wallis H-test was adopted for this metric.

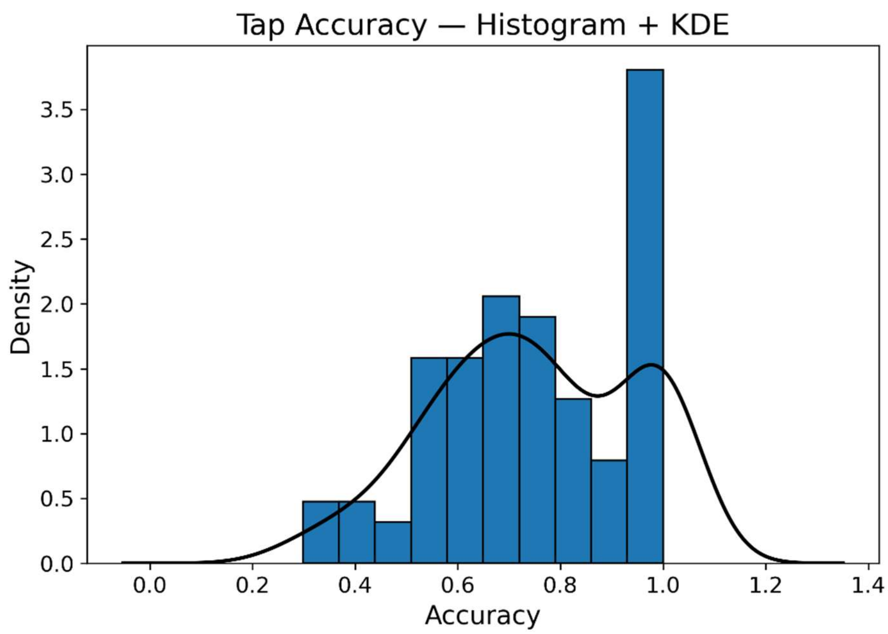

Figure 66 - Histogram + KDE of Tap Accuracy

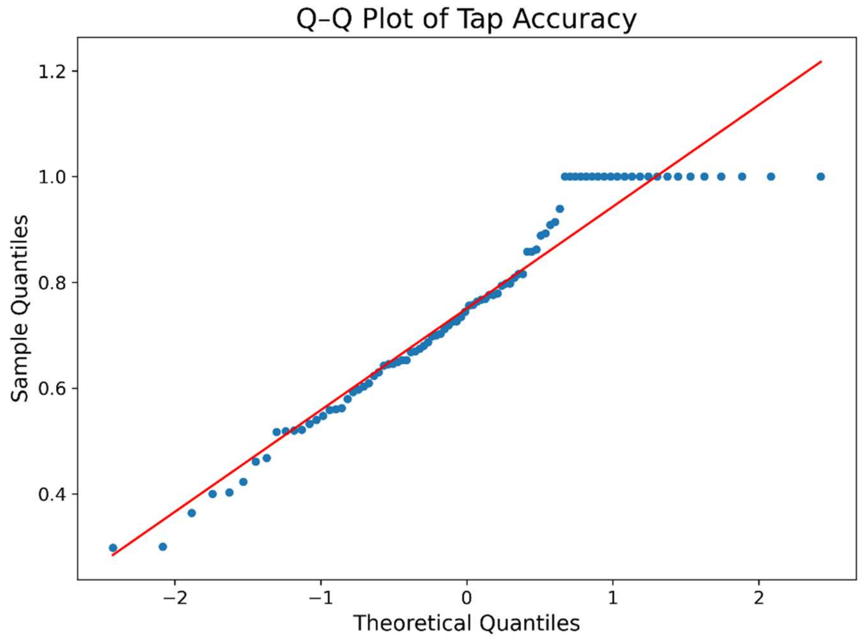

Figure 67 - Q-Q Plot of Tap Accuracy

The omnibus test reports that differences between groups in tap accuracy were significant, $H(3) = 53.23$, $p<0.001$. As expected, the real-world control group was the primary driver of the significant difference between groups. The Dunn's Post Hoc Test for accuracy shows that the haptic fidelity groups (N, L, and H) have no significant differences between each other and report significant difference when compared against the real-world control group. In a discrete gesture like tap, haptic feedback did not significantly enhance tapping accuracy in the virtual world, highlighting that the visual and spatial cues primarily influence tap accuracy.

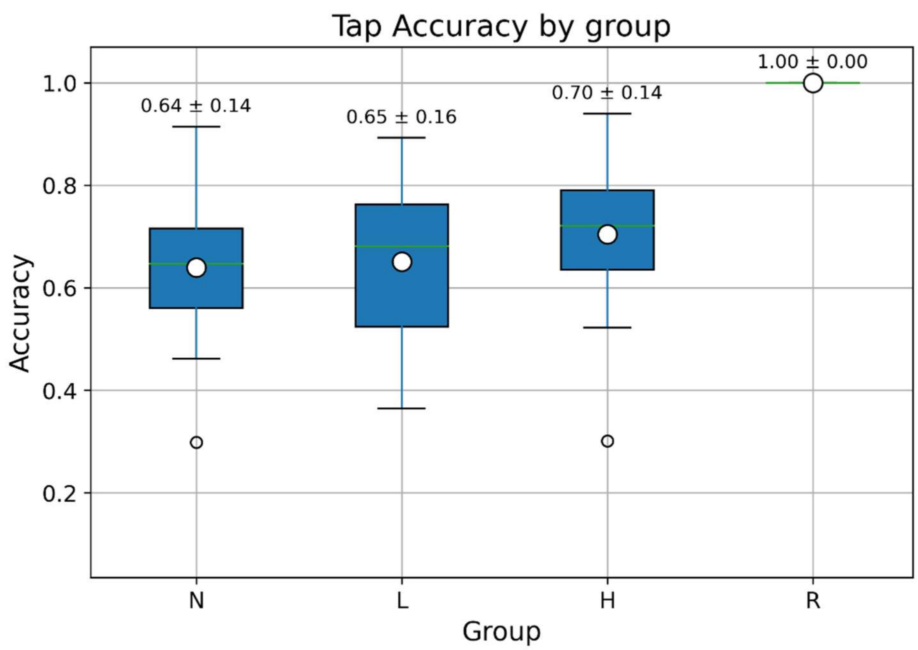

Figure 68 - Tap Accuracy Box Plot

Table 12 - Dunn's Post Hoc Table on Tap Accuracy

Comparison	p-Value	Significance
H vs L	1.0	Not Significant
H vs N	1.0	Not Significant
H vs R	1.90×10^{-6}	Significant
L vs N	1.0	Not Significant
L vs R	1.80×10^{-9}	Significant
N vs R	6.19×10^{-9}	Significant

Error Rate:

The assumption checks for the tap error rate reported a violation of homogeneity of variance ($p < 0.001$). Similar to tap accuracy, the Kruskal-Wallis H test was applied for error rate comparison across the four groups.

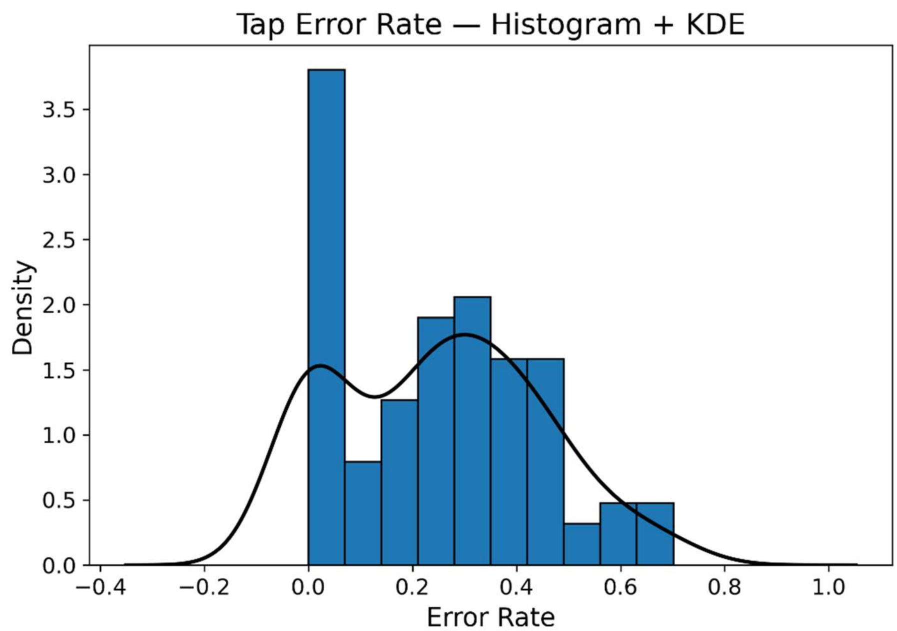

Figure 69 - Histogram + KDE of Tap Error rate

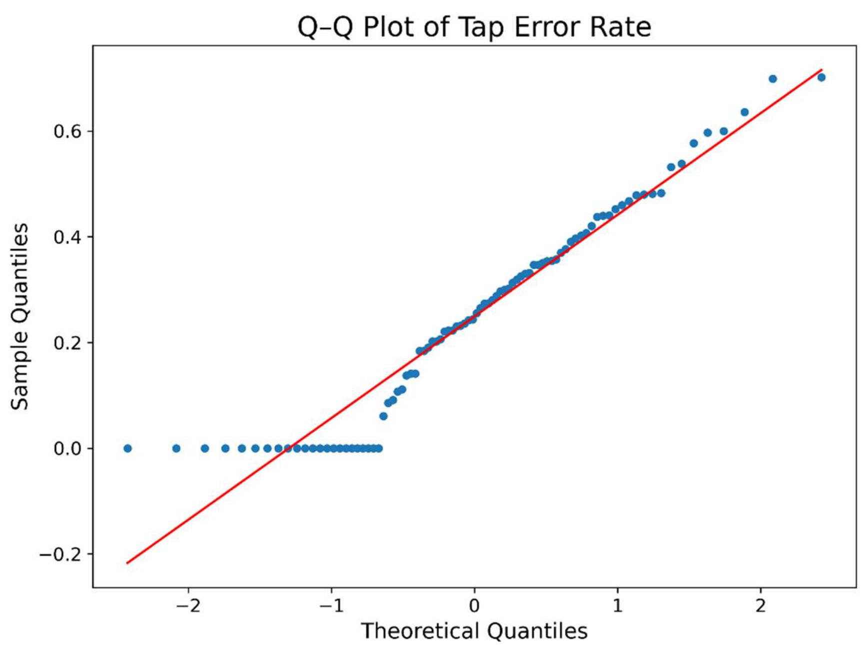

Figure 70 - Q-Q Plot of Tap Error Rate

The omnibus test reported a significant difference between the groups, $H(3) = 53.23$, $p < 0.001$, which is mainly driven by the difference between the real-life group and the other haptic fidelity groups (N, L, and H). The findings show that the participants in the real-world group made no tapping errors, while the groups on the haptic fidelity spectrum did not significantly reduce error rates.

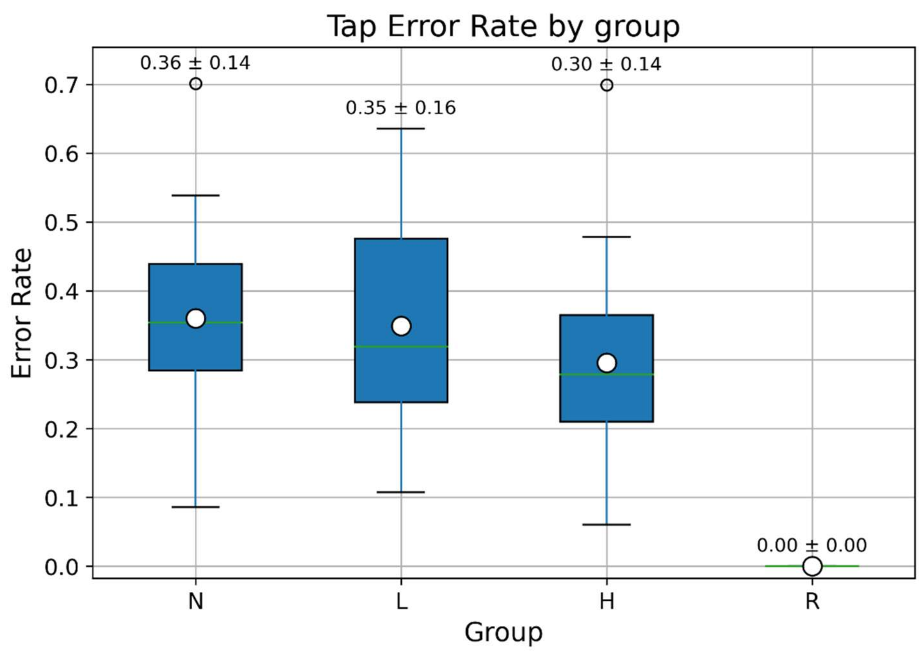

Figure 71 - Tap Error Rate Box Plot

Table 13 - Dunn's Post Hoc Table on Tap Error Rate

Comparison	p-Value	Significance
H vs L	1.0	Not Significant
H vs N	1.0	Not Significant
H vs R	1.90×10^{-6}	Significant
L vs N	1.0	Not Significant
L vs R	1.80×10^{-9}	Significant
N vs R	6.19×10^{-9}	Significant

Task Completion Time:

The assumption checks indicate non-normality in two groups, the high haptic fidelity group and the low haptic fidelity group (Shapiro-Wilk: L and H $p < 0.01$) and unequal variances (Levene $p = 0.0005$). Thus, the task completion time will utilize the Kruskal-Wallis H-test.

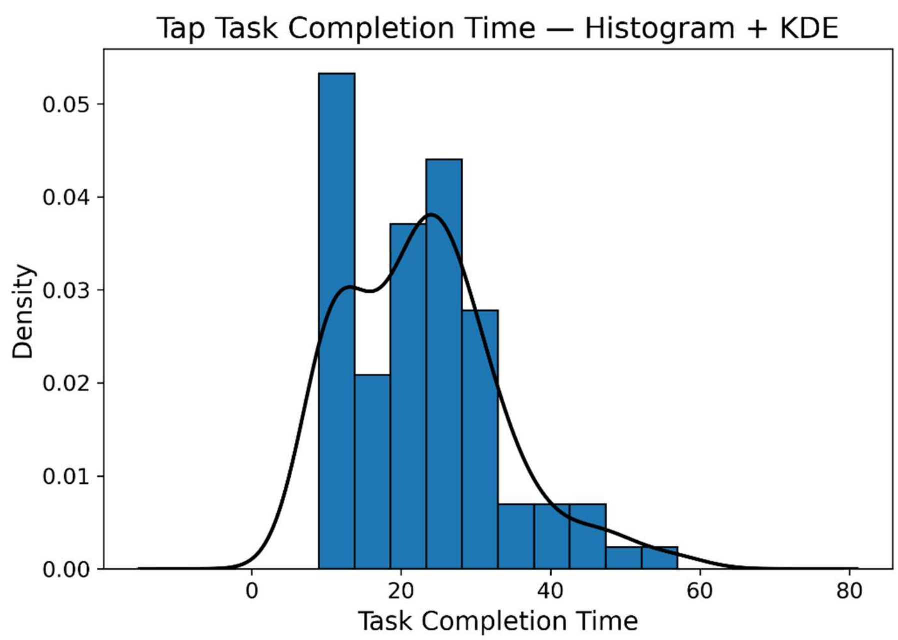

Figure 72 - Histogram + KDE of Tap Task Completion Time

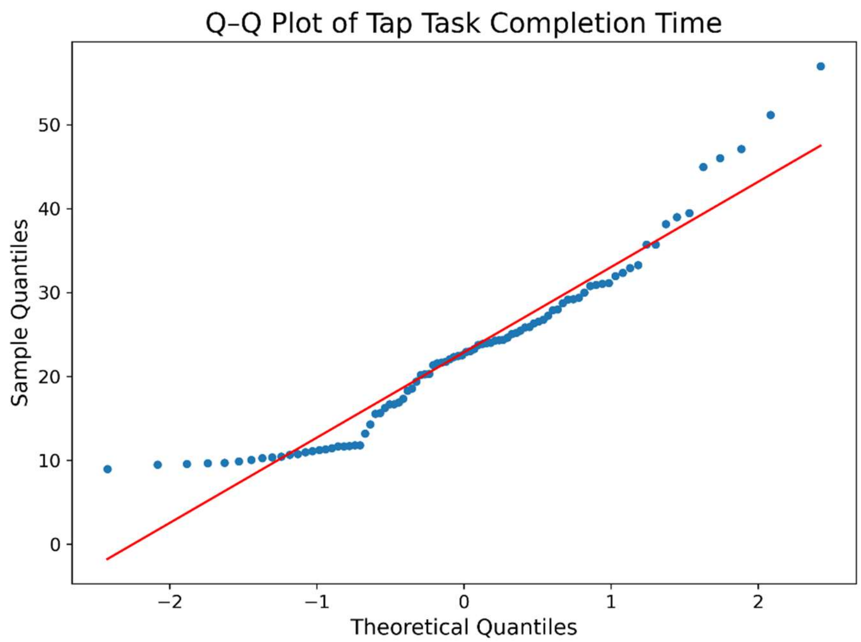

Figure 73 - Q-Q Plot of Tap Task Completion Time

The omnibus test reported a significant difference between the groups, $H(3) = 54.42$, $p < 0.001$. The expectation is that the real-world group would be able to complete the task faster, as demonstrated in the Dunn post hoc test. Additionally, there were no pairwise differences detected among the three haptic fidelity groups. All in all, the real-life group outperformed all haptic fidelity groups, and the haptic fidelity groups did not differ significantly themselves.

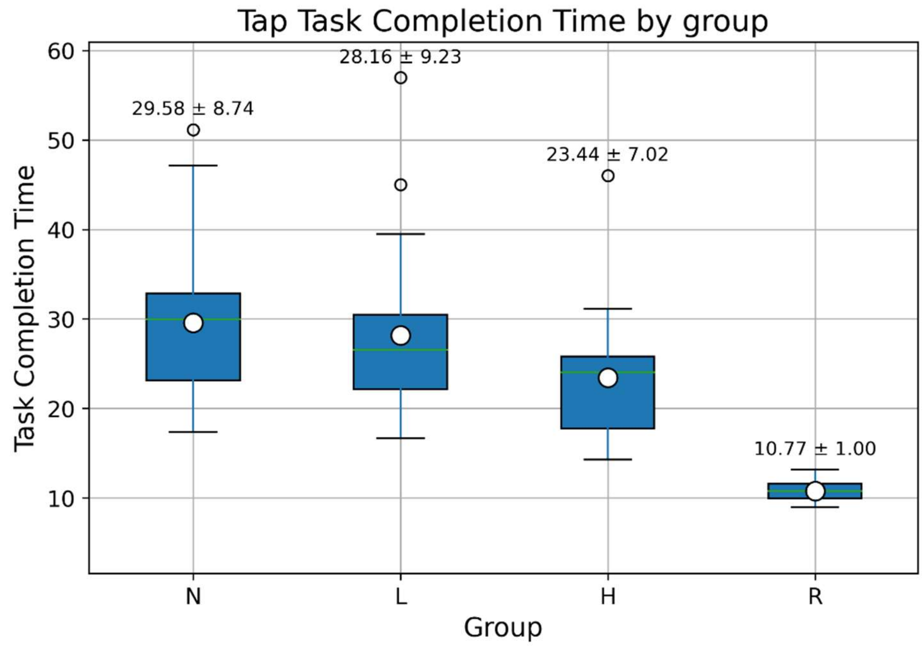

Figure 74 - Tap Task Completion Time Box Plot

Table 14 - Dunn's Post Hoc Table on Tap Task Completion Time

Comparison	p-Value	Significance
H vs L	1.0	Not Significant
H vs N	0.405	Not Significant
H vs R	1.46×10^{-5}	Significant
L vs N	1.0	Not Significant
L vs R	1.78×10^{-9}	Significant
N vs R	1.05×10^{-9}	Significant

Speed:

The assumption checks reported non-normality for at least one group (No haptic feedback group: $p = 0.038$). Meanwhile, Levene's test showed that homoscedasticity is met ($p = 0.77$). Due to the non-normality, the Kruskal-Wallis test was used across groups.

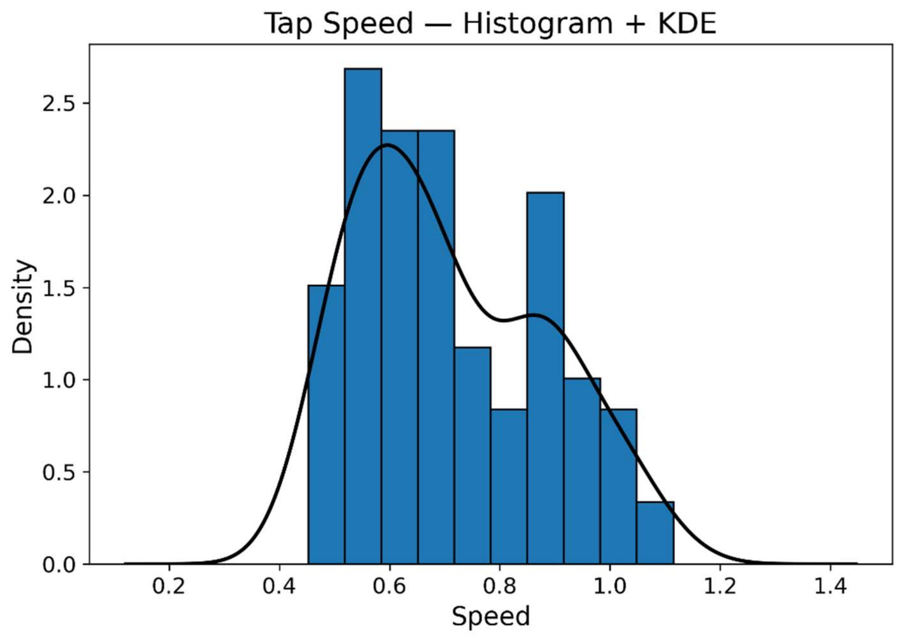

Figure 75 - Histogram + KDE of Tap Speed

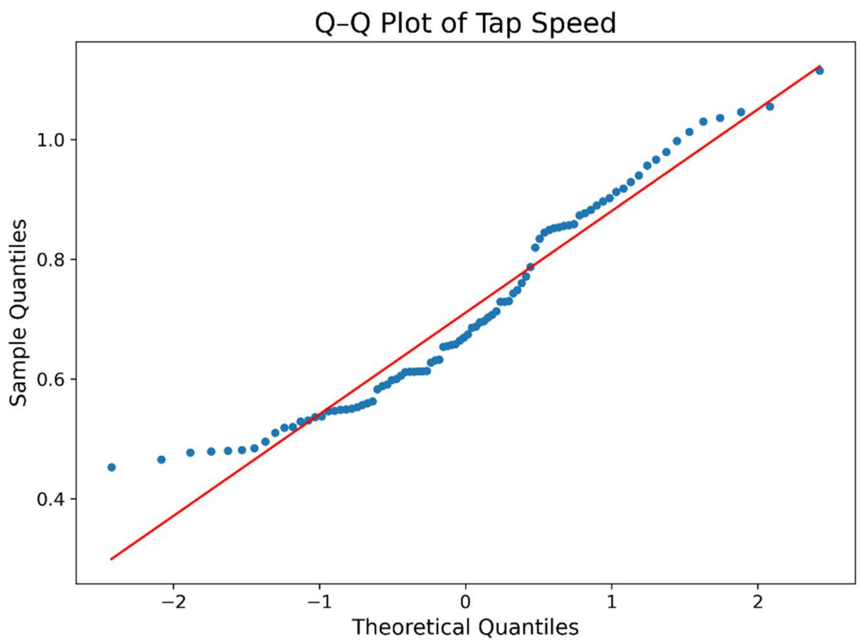

Figure 76 - Q-Q Plot of Tap Speed

Based on the results of the omnibus test, the real-world condition produced significantly faster tap speed than the haptic fidelity conditions (N, L, and H). Additionally, there were no pairwise differences among the haptic fidelity groups. Based on the results, the increase of haptic fidelity did not yield statistically significant differences in speed. This suggests that the level of haptic fidelity alone does not materially change how quick the participants can tap.

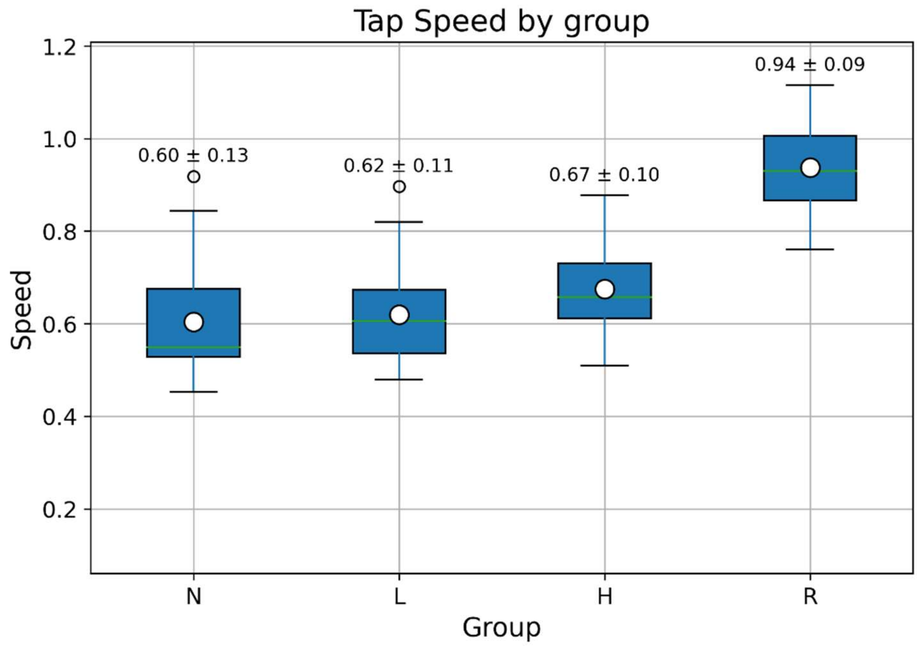

Figure 77 - Tap Speed Box Plot

Table 15 - Dunn's Post Hoc Table on Tap Speed

Comparison	p-Value	Significance
H vs L	0.993	Not Significant
H vs N	0.444	Not Significant
H vs R	4.8×10^{-5}	Significant
L vs N	1.0	Not Significant
L vs R	8.35×10^{-9}	Significant
N vs R	6.30×10^{-9}	Significant

4.3.2 Pan Task

The Pan task is designed for the evaluation of the participant's ability to continuously move objects across the touchscreen surface, which simulates the natural dragging (pan) gesture used in everyday interactions such as scrolling or repositioning items. In contrast to the tap task, which relies on a single discrete point selection, the pan task is a continuous gesture where performance depends on the smooth control, accuracy of the direction, and consistency of the motion over time. The pan task provides insights into how the different groups affect the fine-motor control and movement stability on a touchscreen.

Accuracy:

Due to the nature of the pan task, the assumption checks indicated clear ceiling effects and non-normality. Histogram values were massed at 0.99 – 1.00 and the Q-Q plot flattened at the top. Therefore, the group differences are tested with Kruskal-Wallis H-test.

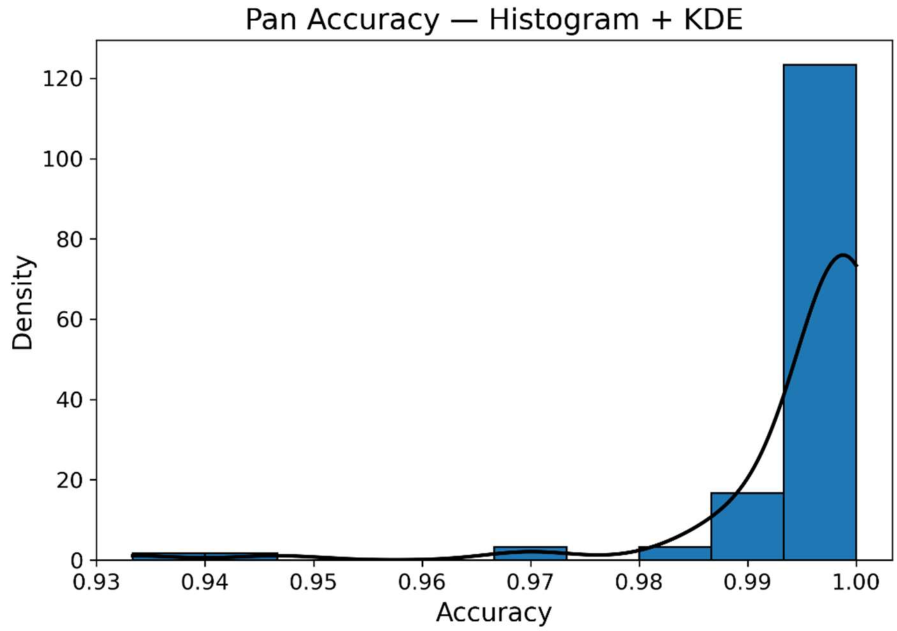

Figure 78 - Histogram + KDE of Pan Accuracy

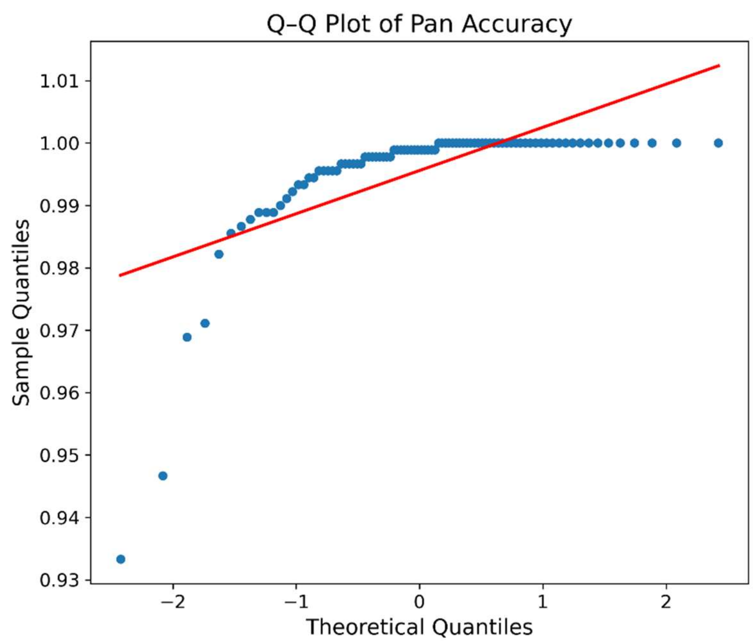

Figure 79 - Q-Q Plot of Pan Accuracy

The omnibus test results reported no significant differences ($p > 0.05$), indicating that there is no detectable effect of haptic feedback on pan accuracy. However, all three haptic fidelity groups matched the real-world group's accuracy. Given the non-significance reported result, no post hoc pairwise comparisons are reported.

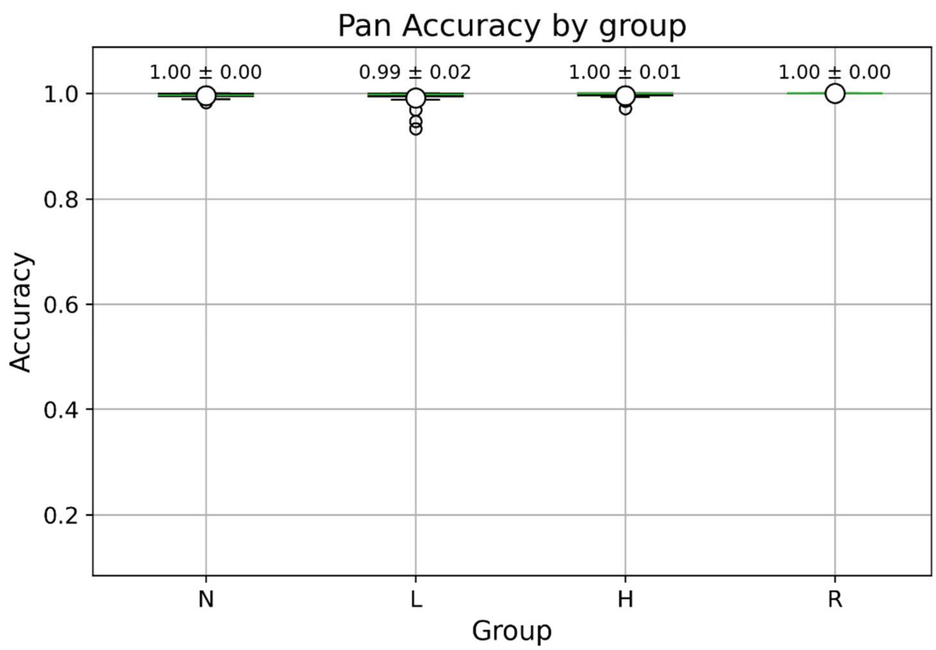

Figure 80 - Pan Accuracy Box Plot

Error Rate:

The assumption tests indicated non-normality and heteroscedasticity, as shown by a histogram concentrated near zero and a Q-Q plot deviating from linearity. Accordingly, the Kruskal-Wallis H-test was used for the assessment of the group differences.

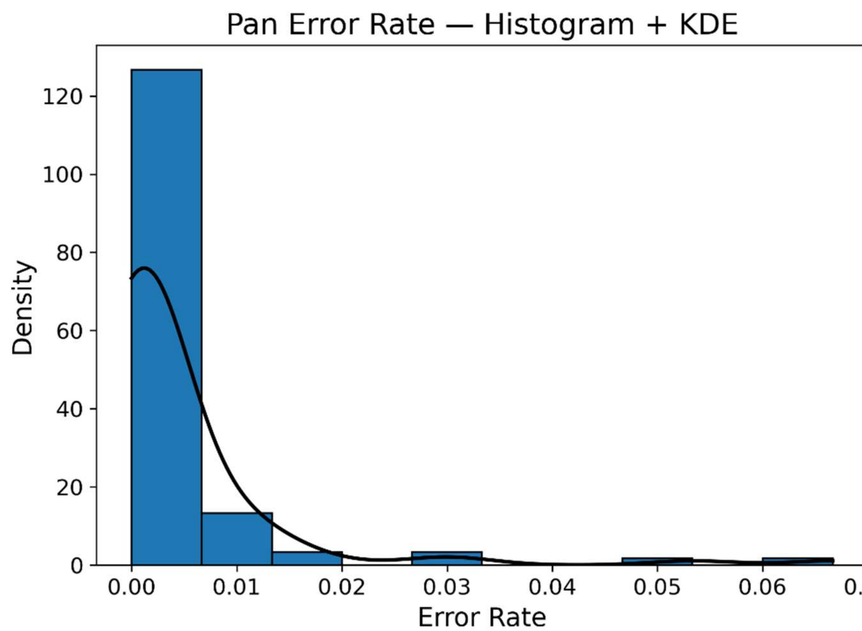

Figure 81 - Histogram + KDE of Pan Error Rate

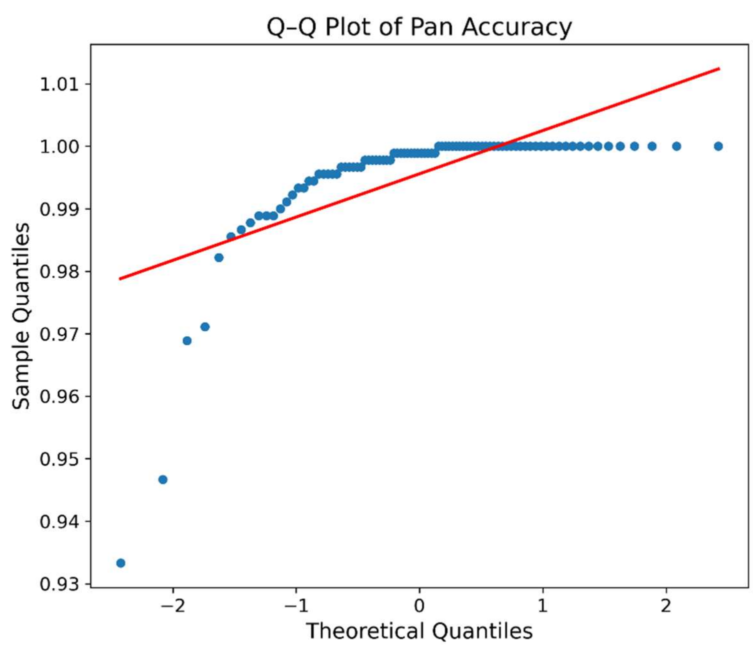

Figure 82 - Q-Q Plot of Pan Error Rate

The omnibus test was non-significant ($p > 0.05$), which suggests that haptic fidelity level did not have a measurable effect on how a participant's error rate changed during the pan task. Therefore, post hoc pairwise test was not performed.

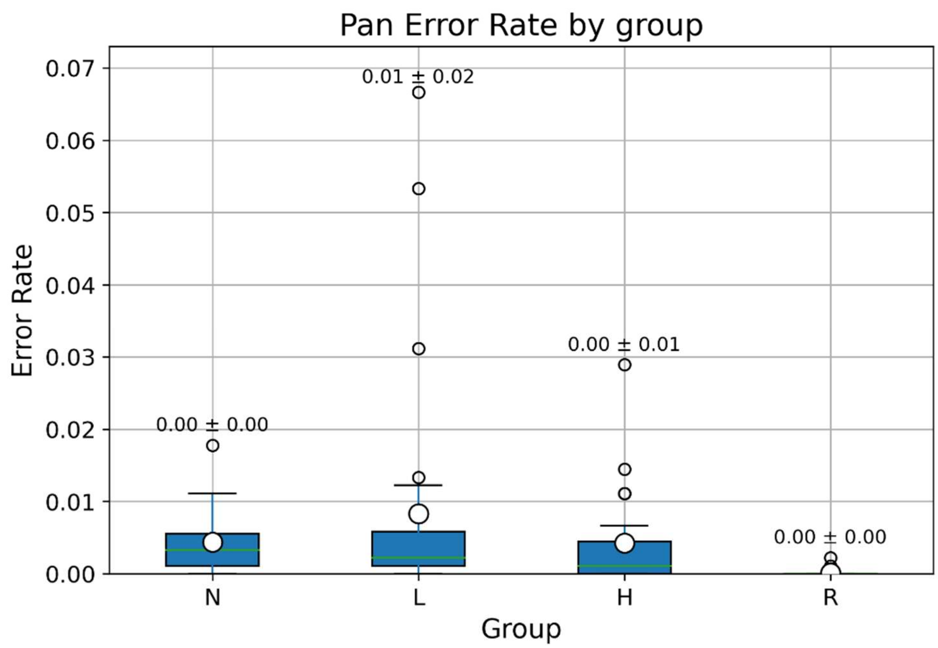

Figure 83 - Pan Error Rate Box Plot

Task Completion Time:

The assumption tests revealed deviations from normality and heteroscedasticity, as noted by the right-skew distribution of the histogram and the upward deviation of the Q-Q plot. Thus, task completion time will be evaluated using the Kruskal-Wallis H-test.

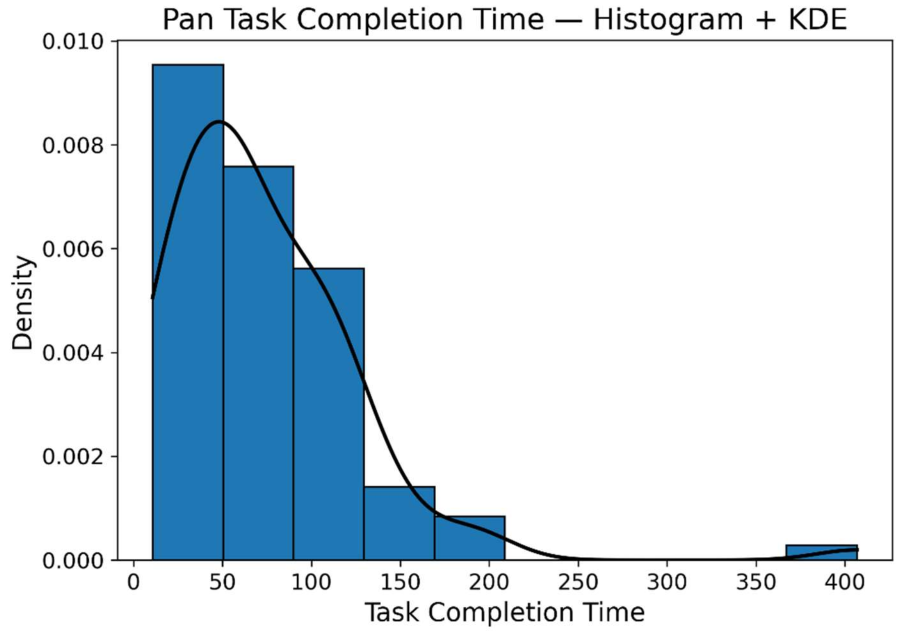

Figure 84 - Histogram + KDE of Pan Task Completion Time

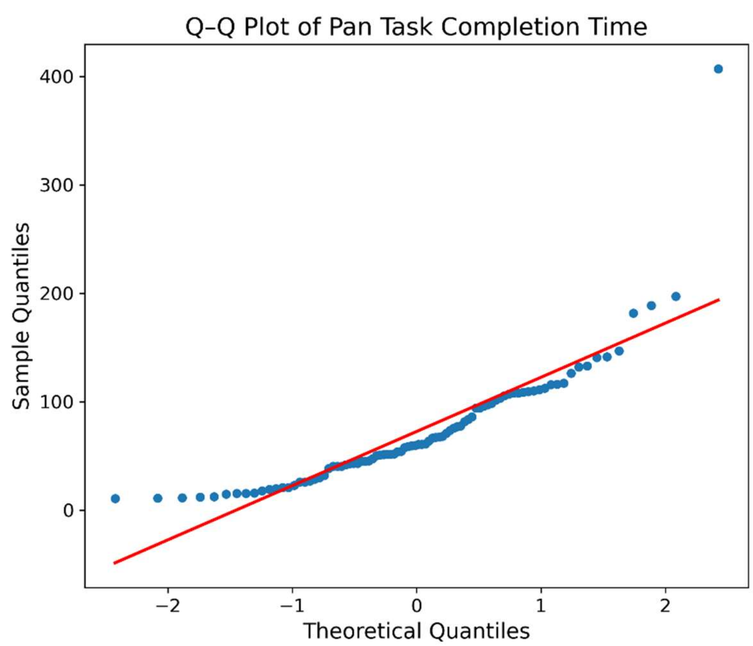

Figure 85 - Q-Q Plot of Pan Task Completion Time

The omnibus test results were significant ($p < 0.001$), which indicates that there is at least one condition that has a different median completion time. The results of the Dunn-Bonferroni post hoc test shows that the real-world control group (R) completed the pan task significantly faster than the haptic fidelity groups. Additionally, the post hoc test revealed that there are no significant differences found among the haptic fidelity conditions themselves. The results suggest that there might be a physical tactile interaction and reduced latency in real-world environments substantially enhance the efficiency of pan task execution compared to the haptic fidelity conditions.

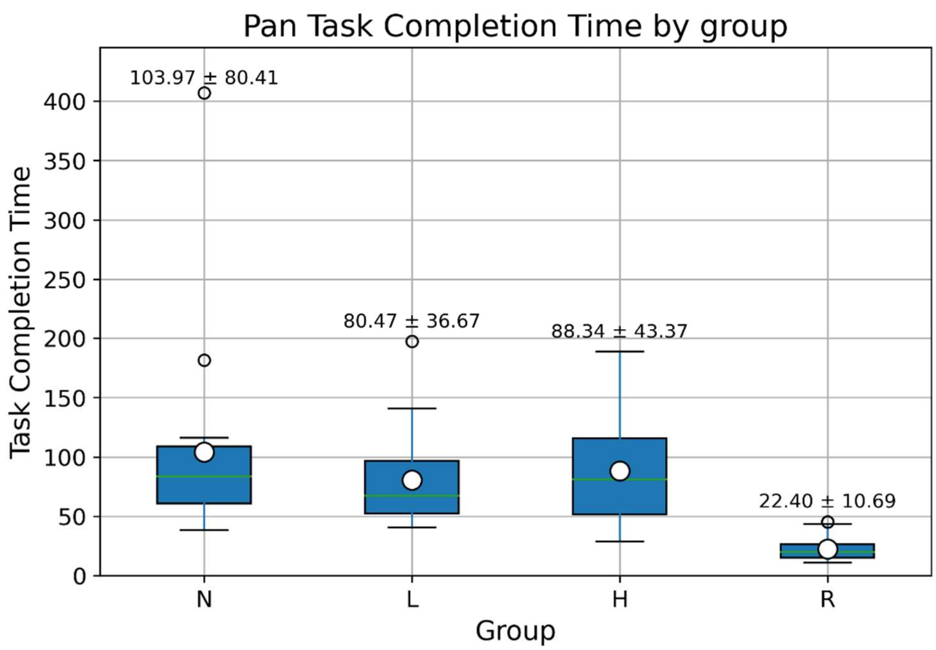

Figure 86 - Pan Task Completion Time Box Plot

Table 16 - Dunn's Post Hoc Table on Pan Task Completion Time

Comparison	p-Value	Significance
H vs L	1.0	Not Significant
H vs N	1.0	Not Significant
H vs R	9.70×10^{-8}	Significant
L vs N	1.0	Not Significant
L vs R	4.73×10^{-7}	Significant
N vs R	3.08×10^{-8}	Significant

Speed:

Assumption checks revealed that the data were non-normal and had unequal variances across the groups. Similar to pan task completion time, the histogram was right skewed and the Q-Q plot deviated from the diagonal. Therefore, the Kruskal-Wallis H-test is used to assess the differences between groups.

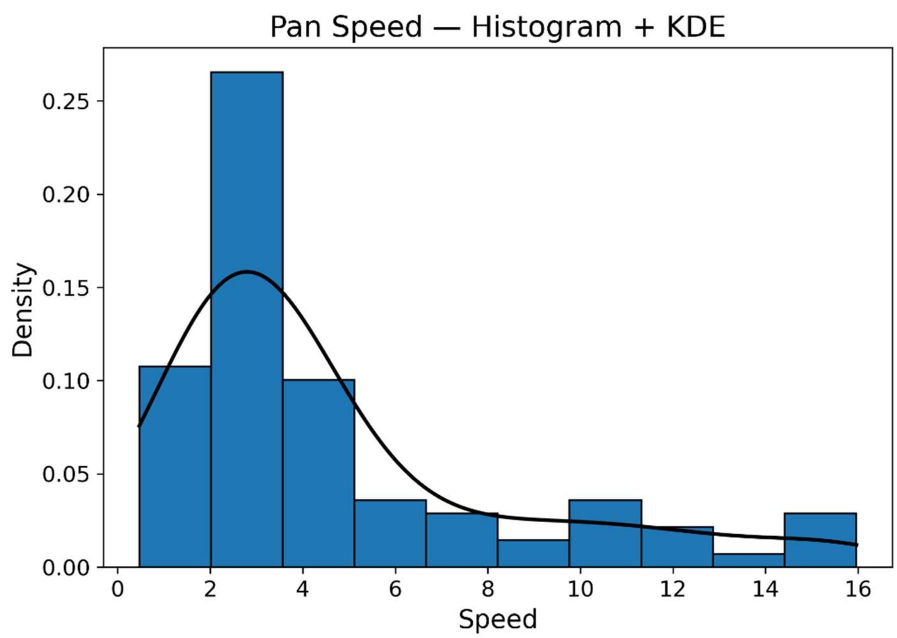

Figure 87 - Histogram + KDE of Pan Speed

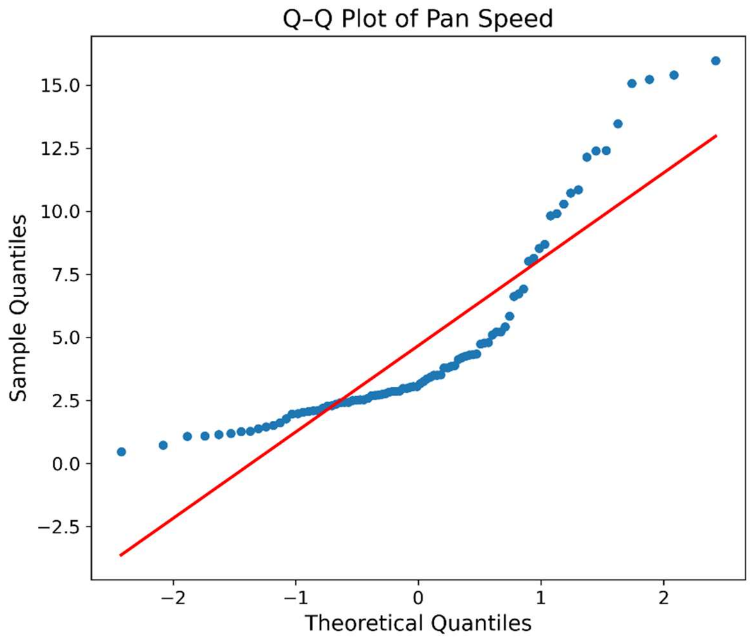

Figure 88 - Q-Q Plot of Pan Speed

The results of the Kruskal-Wallis H-test showed that there is significant difference in between groups ($p < 0.001$). the results of the Dunn's post hoc test revealed that the real-world group achieved significantly higher pan speed than the haptic fidelity conditions. Among the haptic fidelity groups, there were no significant differences. The results show that the pan speed in the real-world group was three times faster than the haptic conditions, this shows that despite the inclusion of haptic feedback, virtual environments might still introduce latency or precision constraints that reduce overall motion efficiency compared to real-world performance.

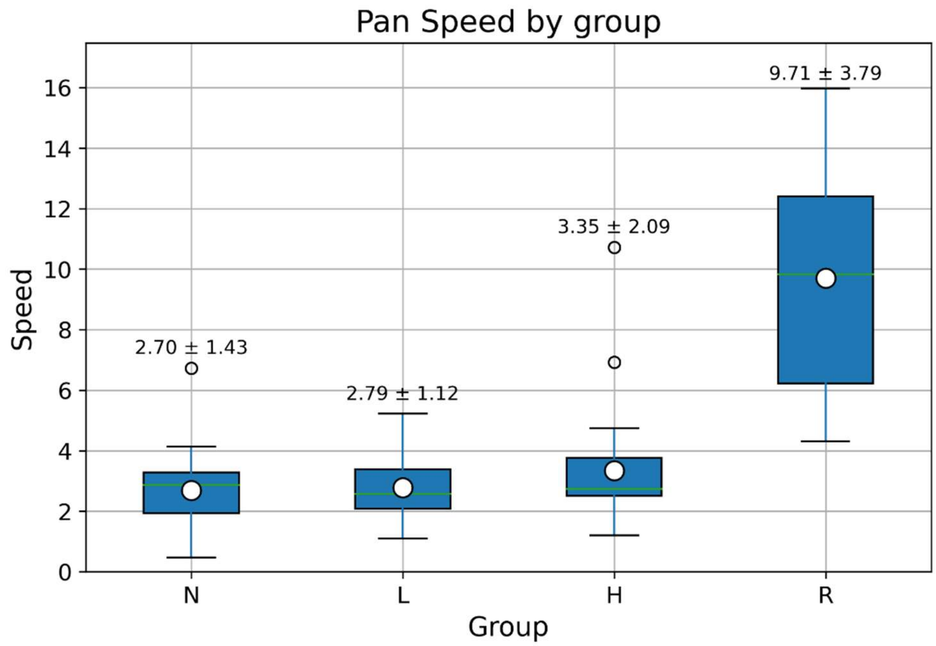

Figure 89 - Pan Speed Box Plot

Table 17 - Dunn's Post Hoc Table on Pan Speed

Comparison	p-Value	Significance
H vs L	1.0	Not Significant
H vs N	1.0	Not Significant
H vs R	3.27×10^{-6}	Significant
L vs N	1.0	Not Significant
L vs R	1.76×10^{-8}	Significant
N vs R	1.74×10^{-6}	Significant

4.3.3 Pinch Task

The pinch task is designed to evaluate the participant's ability to perform a two-finger pinch gesture to resize the objects displayed on the screen. In contrast to the tap and pan tasks, which rely on a single point input, the pinch represents a continuous bimanual coordination gesture that relies on the spatial precision and dynamic properties of haptic feedback. The performance analysis of pinch provides insights into how accurately and efficiently users can modulate bimanual grip-based interactions in virtual reality compared to real-world settings.

Accuracy:

The distribution of accuracy scores was left-skewed, with the majority of participants achieving very high accuracy across all conditions. The Shapiro-Wilk tests report deviations from normality in some groups, and Levene's test showed that variances are unequal, confirming that a non-parametric test is more appropriate (Kruskal-Wallis H-test).

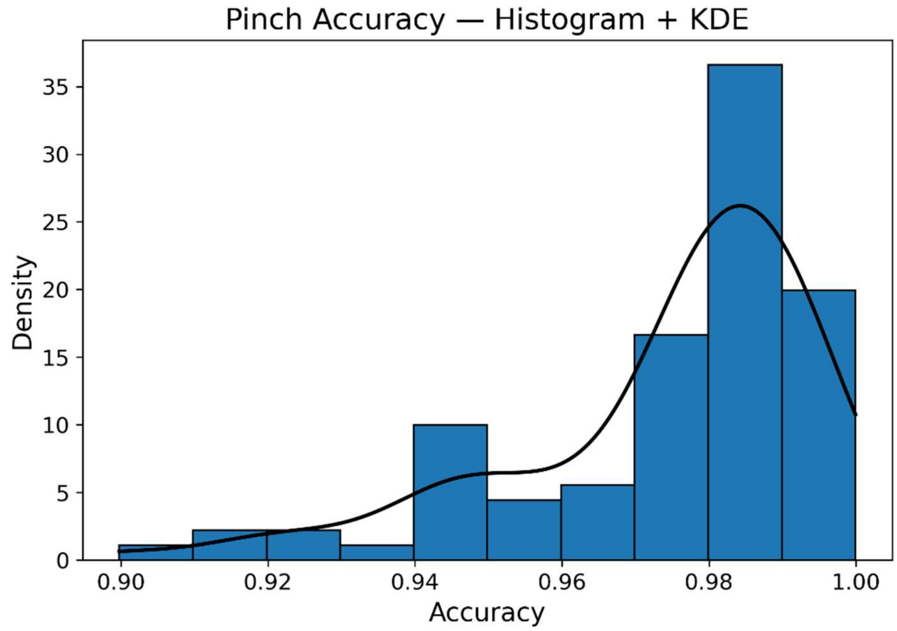

Figure 90 - Histogram + KDE of Pinch Accuracy

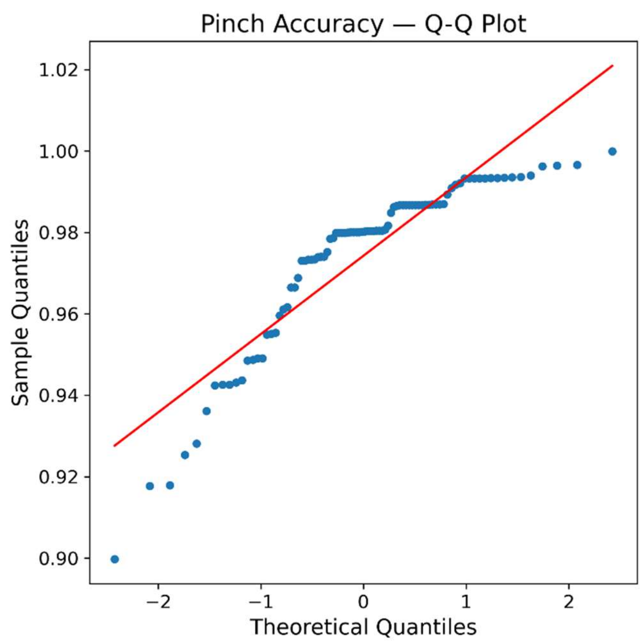

Figure 91 - Q-Q Plot of Pinch Accuracy

The Kruskal-Wallis H-test revealed that there is a significant difference between groups, $H(3) = 12.06$, $p = 0.007$ ($p<0.01$), indicating that at least one group has differed in pinch accuracy. The results of the post hoc test showed that the real-world group (R) achieved significantly higher accuracy compared to the no haptic feedback (N) and low haptic fidelity (L) groups. However, there were no significant differences found between the high haptic fidelity group (H) and the real-world group (R), nor amongst the three haptic fidelity groups themselves. The results suggest that the increase in haptic fidelity leads in a narrowing in the accuracy gap between the virtual and real-world interactions for bimanual pinch gesture.

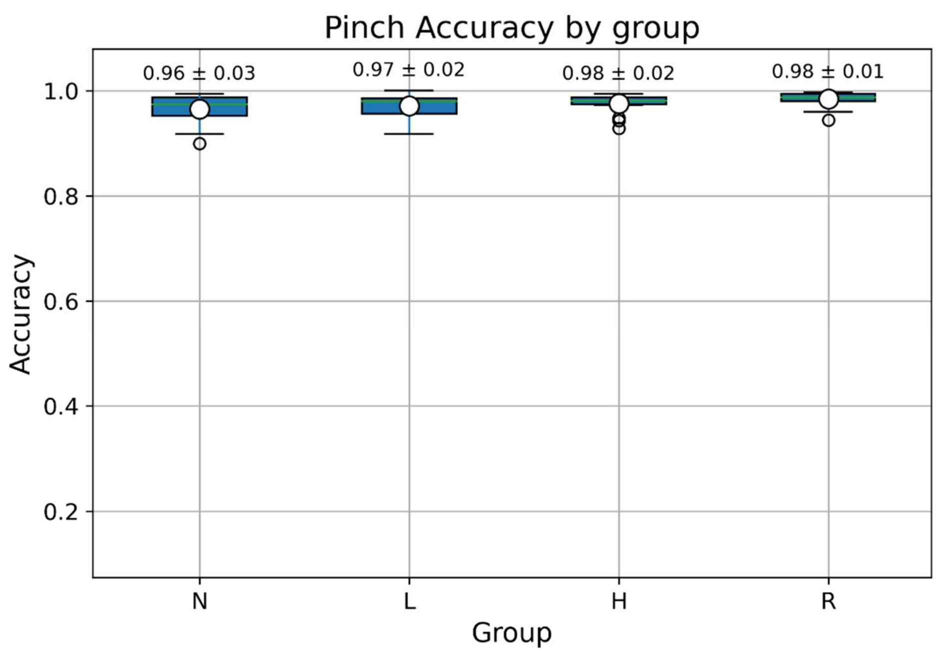

Figure 92 - Pinch Accuracy Box Plot

Table 18 - Dunn's Post Hoc Table on Pinch Accuracy

Comparison	p-Value	Significance
H vs L	1.0	Not Significant
H vs N	1.0	Not Significant
H vs R	0.30	Not Significant
L vs N	1.0	Not Significant
L vs R	0.0209	Significant
N vs R	0.0129	Significant

Error Rate:

The assumption checks indicated violations of normality across all groups, as shown in the histogram and Q-Q plot. The Levene's test showed that the assumption of equal variances was met. Therefore, the Kruskal-Wallis H-test was performed for the evaluation of differences across the groups.

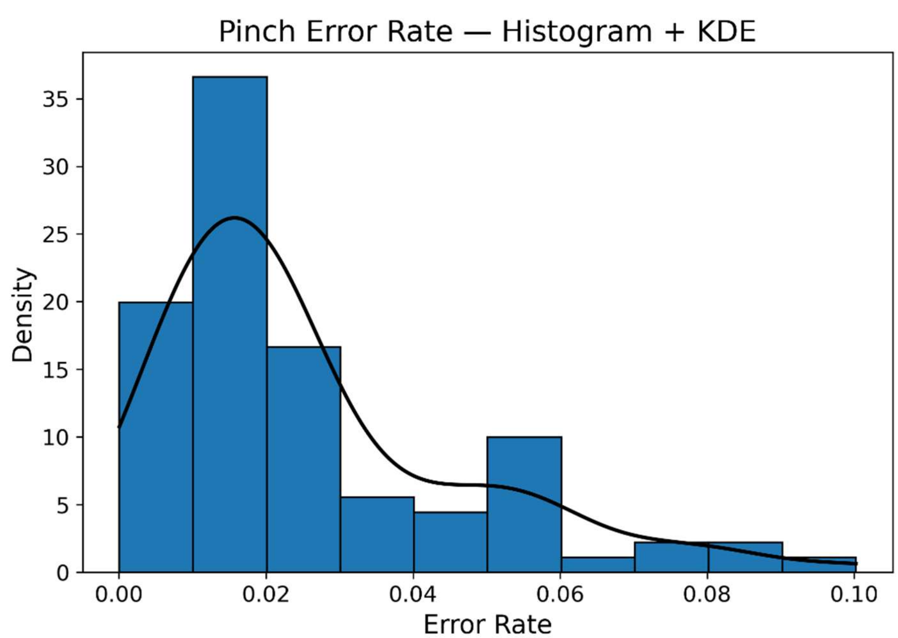

Figure 93 - Histogram + KDE of Pinch Error Rate

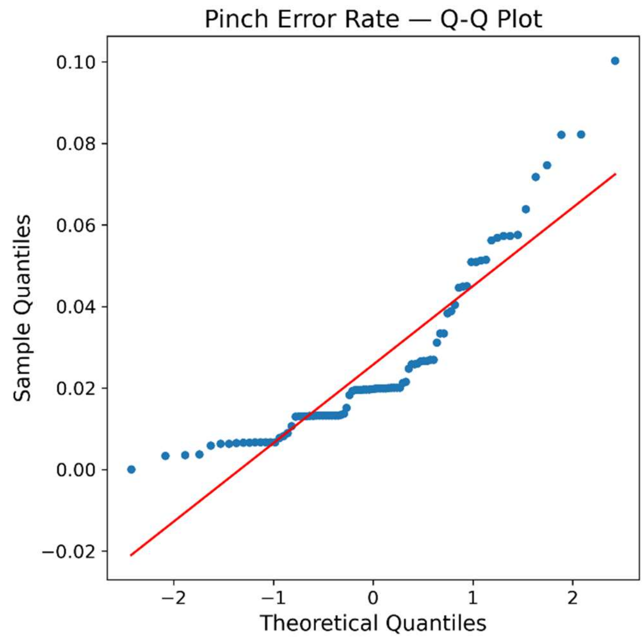

Figure 94 - Q-Q Plot of Pinch Error Rate

The omnibus analysis revealed that there is a significant difference between groups, H(3) = 11.79, p = 0.008 (p <0.001). The post hoc analysis dictates that the real-world condition (R) made significantly less errors compared to the no haptic feedback (N) and low haptic fidelity (L) groups. Similar to pinch accuracy, there were no significant differences reported between the high haptic (H) and the real-world (R) conditions, or among the three haptic fidelity conditions. These results suggest that higher haptic fidelity leads to fewer errors.

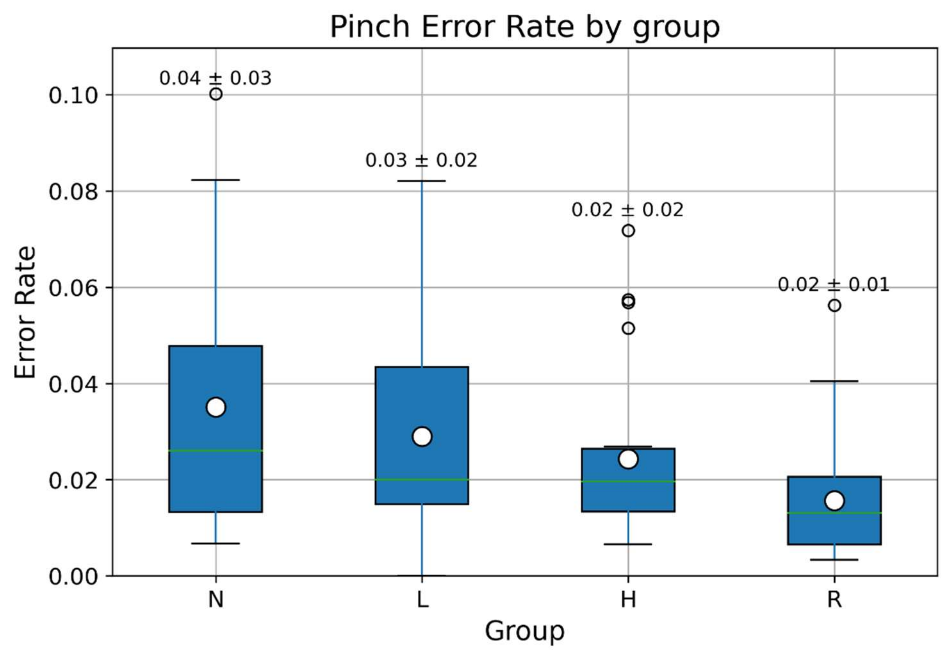

Figure 95 - Pinch Error Rate Box Plot

Table 19 - Dunn's Post Hoc Table on Pinch Error Rate

Comparison	p-Value	Significance
H vs L	1.0	Not Significant
H vs N	1.0	Not Significant
H vs R	0.267	Not Significant
L vs N	1.0	Not Significant
L vs R	0.0188	Significant
N vs R	0.0179	Significant

Task Completion Time:

The assumption checks for the task completion time indicate deviations from normality, with a strong positive skew visible in the histogram and Q-Q plots. The Levene's test confirmed that the variances were homogeneous across the four conditions. Based on the results, the Kruskal-Wallis H-test was used for the omnibus analysis across the groups.

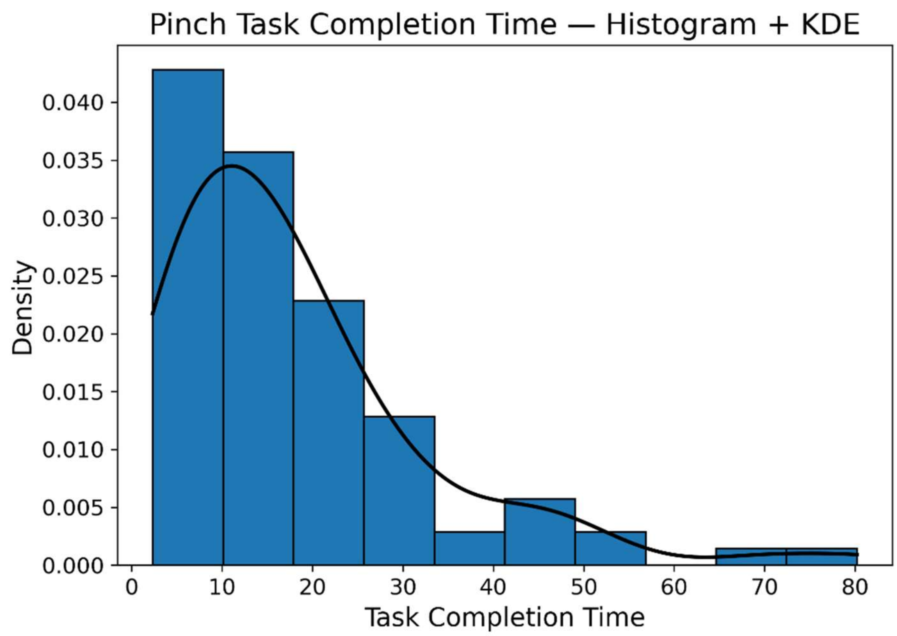

Figure 96 - Histogram + KDE of Pinch Task Completion Time

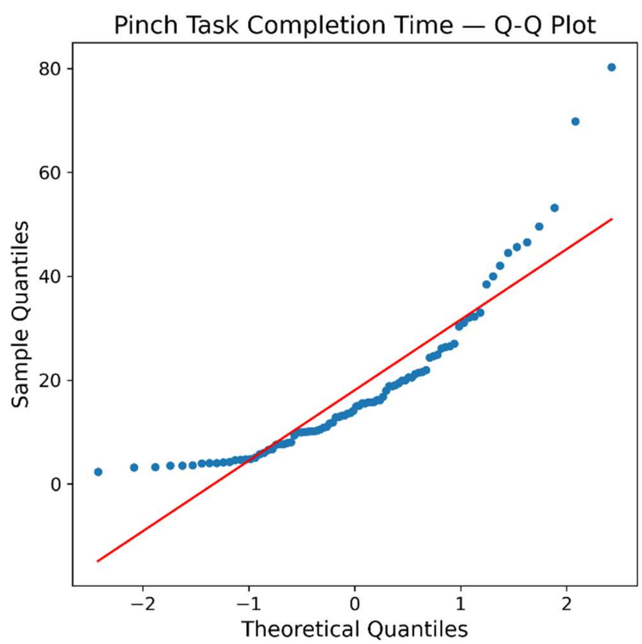

Figure 97 - Q-Q Plot of Pinch Task Completion Time

The omnibus test showed H(3) = 54.12, $p = 3.71\times10^{-12}$ ($p < 0.001$), indicating that differences existed in the task completion times across the four conditions. Post hoc comparisons revealed that the real-world condition (R) significantly outperformed all three haptic fidelity conditions. Additionally, there were no significant differences reported among the haptic fidelity conditions themselves. The results showed that haptic fidelity conditions did not directly improve task completion times and lagged behind the real-world condition.

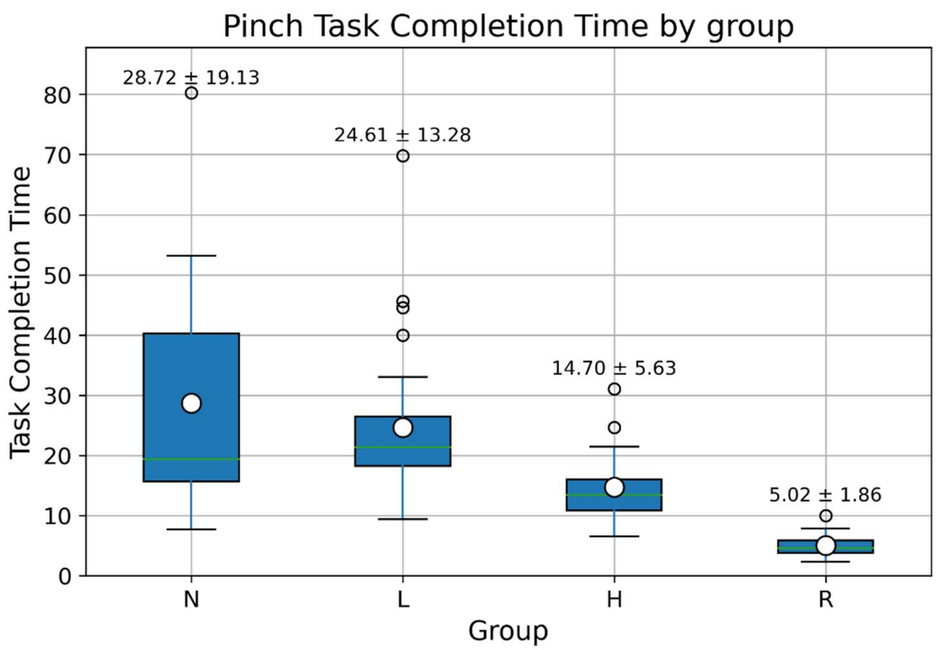

Figure 98 - Pinch Task Completion Time Box Plot

Table 20 - Dunn's Post Hoc Table on Pinch Task Completion Time

Comparison	p-Value	Significance
H vs L	0.101	Not Significant
H vs N	0.172	Not Significant
H vs R	0.0002	Significant
L vs N	1.0	Not Significant
L vs R	1.06×10^{-10}	Significant
N vs R	3.68×10^{-9}	Significant

Speed:

Assumption checks reported that speed values were non-normal across all groups. Meanwhile the Levene's test confirmed that group variances were homogeneous. Therefore, speed was compared using Kruskal-Wallis H-test across the four conditions.

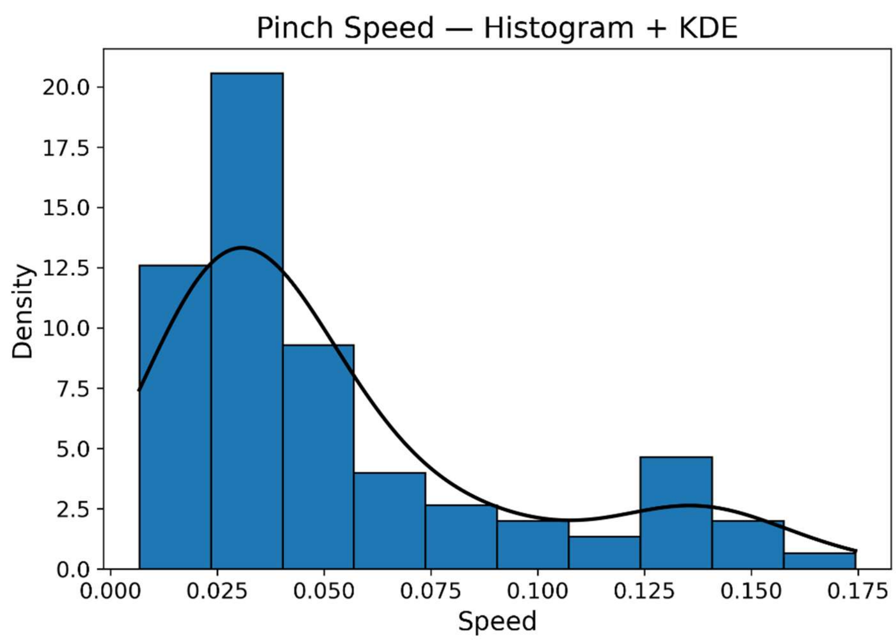

Figure 99 - Histogram + KDE of Pinch Speed

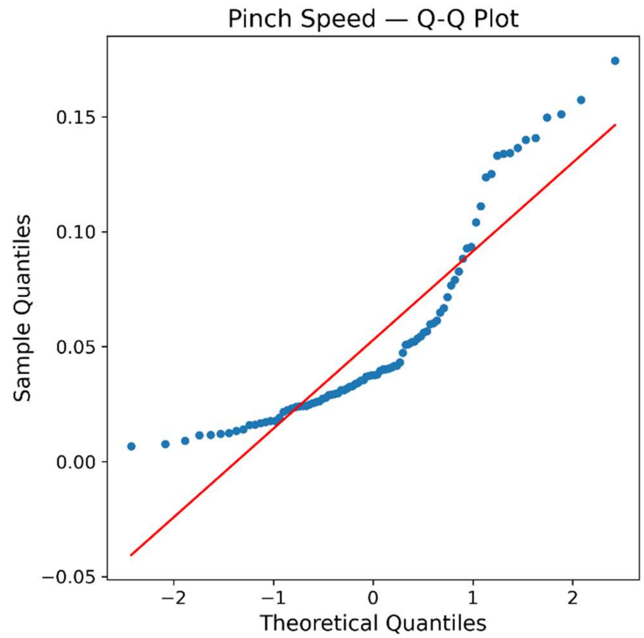

Figure 100 - Q-Q Plot of Pinch Speed

The Kruskal-Wallis H-test showed that there were significant differences between groups, H (3) = 54.18, $p = 3.91\times10^{-12}$, which is an indication that there is a variation in speed by condition. The pairwise comparison done using the Dunn-Bonferroni post hoc test showed that the real-world group was significantly faster than the other conditions. Additionally, there were no significant differences found among the haptic fidelity conditions. These results mirror task completion time findings, showing that haptic fidelity did not improve pinch execution speed to the level of real-world performance.

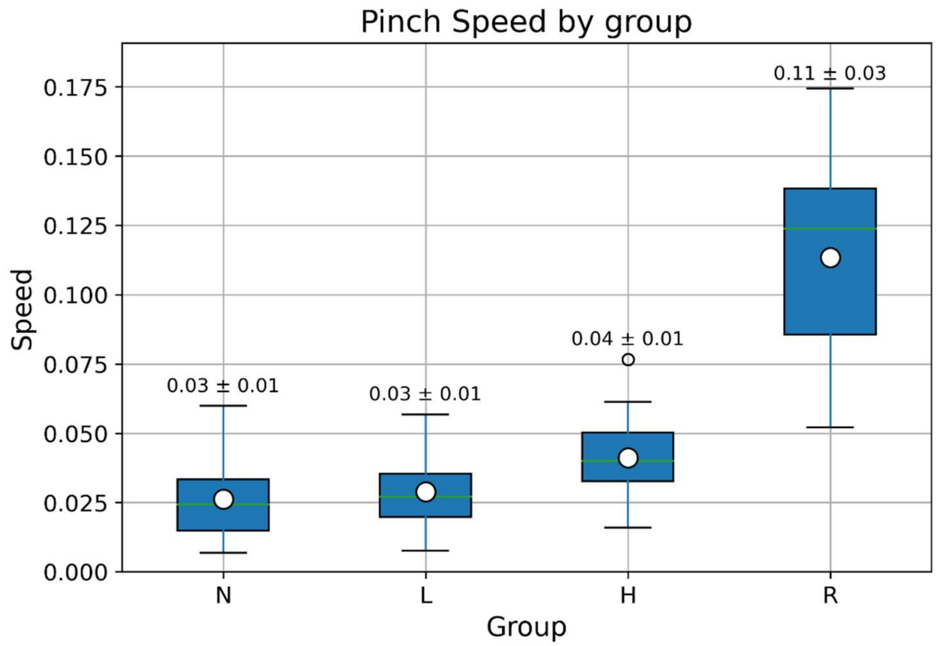

Figure 101 - Pinch Speed Box Plot

Table 21 - Dunn's Post Hoc Table on Pinch Speed

Comparison	p-Value	Significance
H vs L	0.202	Not Significant
H vs N	0.097	Not Significant
H vs R	0.0002	Significant
L vs N	1.0	Not Significant
L vs R	5.05×10^{-10}	Significant
N vs R	7.14×10^{-10}	Significant

4.3.4 Swipe Task

The swipe task requires the participants to perform a direction based horizontal motion across the tablet surface to move through an e-book's pages. This task evaluated participants' ability to execute smooth directional gestures while maintaining control over the gesture amplitude and its consistency. The swipe gesture compared to the previously mentioned gestures requires sustained hand movement and spatial coordination rather than fine-grained precision and control. The following sections present the statistical analysis of swipe accuracy, error rate, task completion time, and swipe speed across all of the four experimental conditions.

Accuracy:

The assumption checks for the swipe accuracy showed that the data violated normality across all groups, as it is demonstrated by the histogram's distribution and Q-Q plots. Moreover, the data confirmed that it meets the assumption of equal variances. Based on these results, the Kruskal-Wallis H-test was used for the comparison of the group medians.

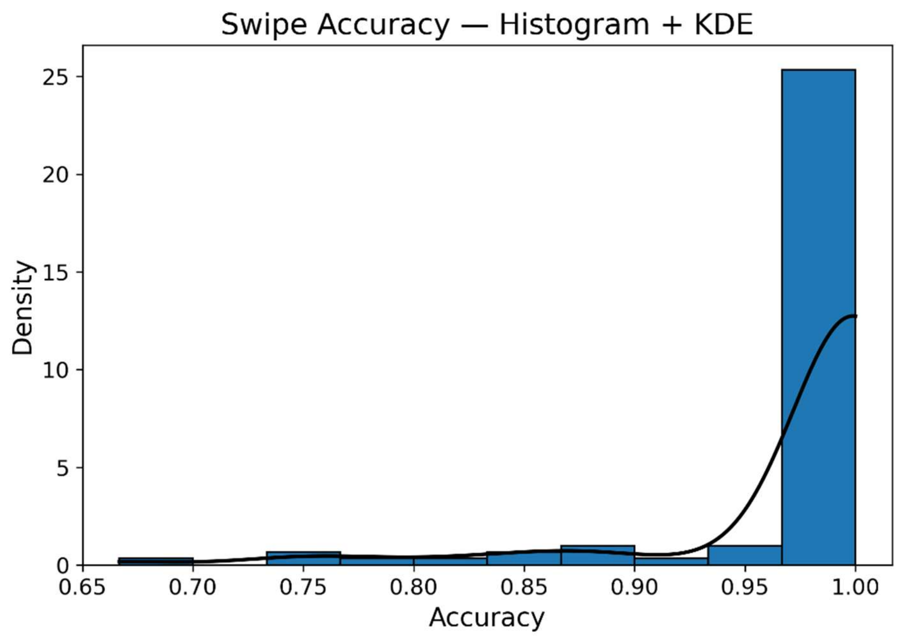

Figure 102 - Histogram + KDE of Swipe Accuracy

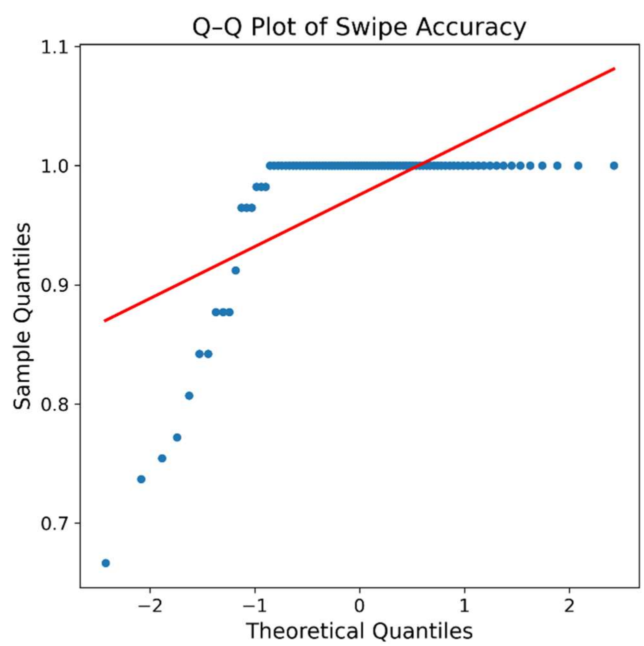

Figure 103 - Q-Q Plot of Swipe Accuracy

The Kruskal-Wallis test results revealed no statistically significant differences among all four groups H(3) = 2.278, p = 0.517, which suggests that the swipe accuracy was comparable between the four conditions. Overall, the accuracy rates were high across conditions, suggesting that the swipe gesture was performed reliably regardless of the haptic fidelity chosen. Based on the omnibus results, no pairwise post hoc tests were performed.

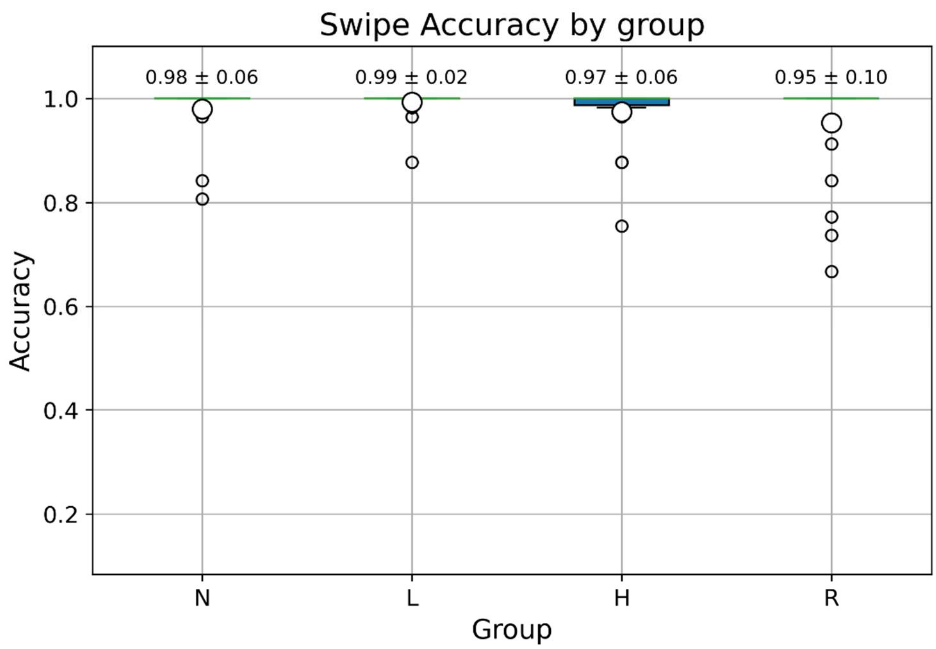

Figure 104 - Swipe Accuracy Box Plot

Error Rate:

The assumption check indicated non-normality across all groups, with a positively skewed distribution shown in the histogram and Q-Q plot. The swipe error rate data showed equality of variances among the groups. Therefore, the Kruskal-Wallis H-test was used to compare the median error rates across the conditions.

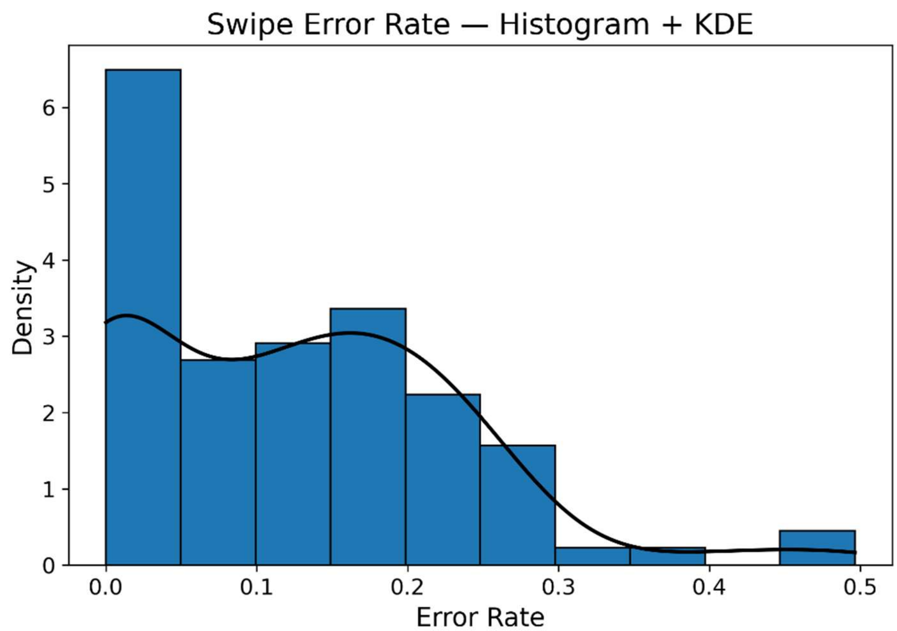

Figure 105 - Histogram + KDE of Swipe Error Rate

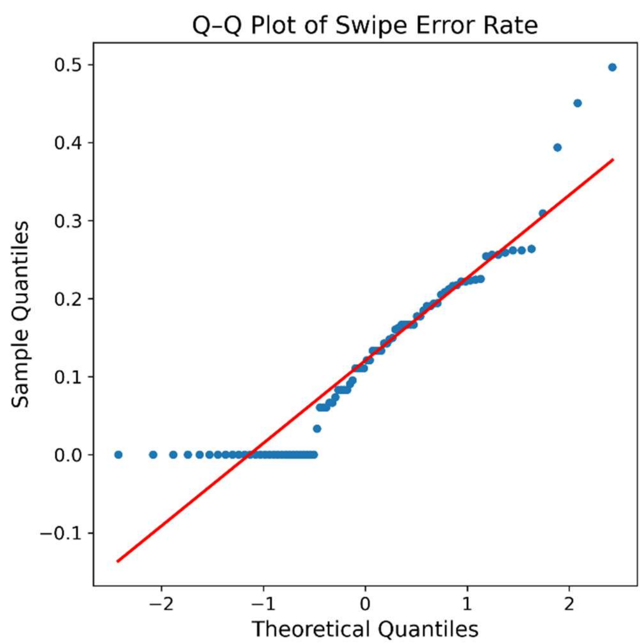

Figure 106 - Q-Q Plot of Swipe Error Rate

The results of the omnibus test show that there are statistically significant differences among the four groups, $H(3) = 10.46$, $p = 0.015$. The Dunn-Bonferroni post hoc comparisons revealed that the real-world condition (R) produced lower error rates than the no haptic feedback (N), whereas the high-fidelity condition (H) and low haptic fidelity (L) groups were not statistically different from the real-world condition. Moreover, the pairwise comparisons among the three haptic fidelity groups themselves were not significant. These results suggest that the addition of haptic feedback brings virtual swipe on a touchscreen to lower error rates comparable to the real-world baseline.

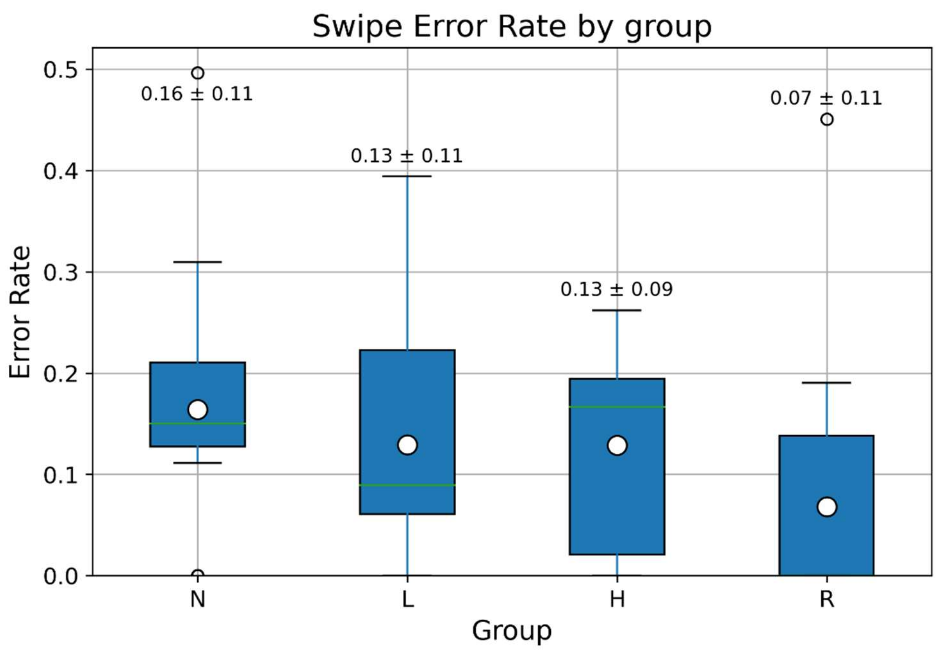

Figure 107 - Swipe Error Rate Box Plot

Table 22 - Dunn's Post Hoc Table on Swipe Error Rate

Comparison	p-Value	Significance
H vs L	1.0	Not Significant
H vs N	1.0	Not Significant
H vs R	0.091	Not Significant
L vs N	1.0	Not Significant
L vs R	0.119	Not Significant
N vs R	0.019	Significant

Task Completion Time:

The assumption checks revealed non-normal distributions across the groups as demonstrated by the histogram and Q-Q plot, while Levene's test confirmed the homogeneity of variances. The Kruskal-Wallis H-test was used to analyze the group effects on swipe task completion time.

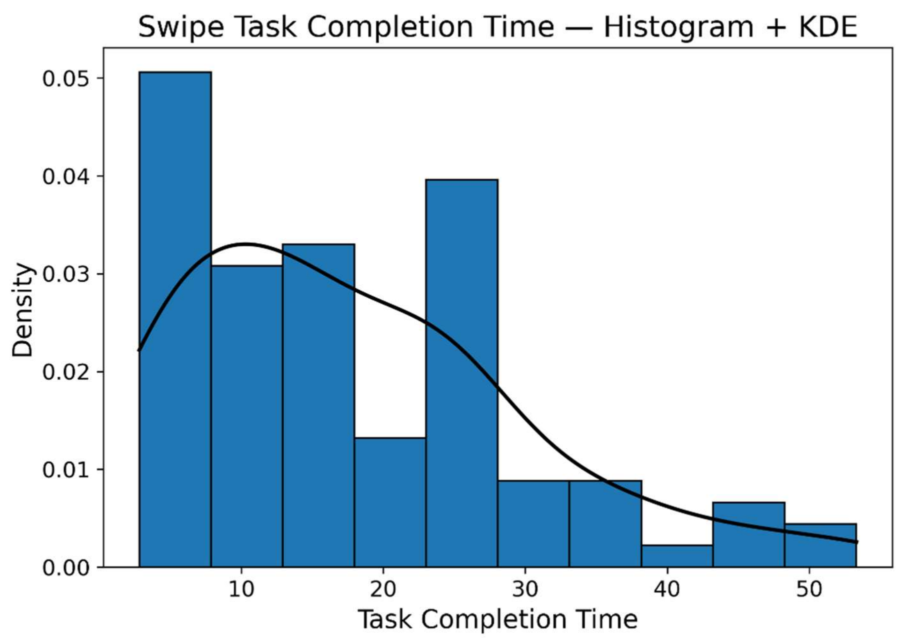

Figure 108 - Histogram + KDE of Swipe Task Completion Time

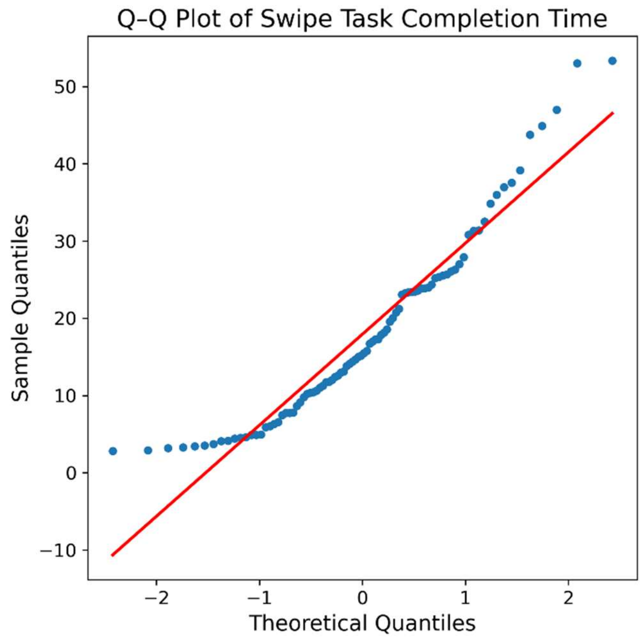

Figure 109 - Q-Q Plot of Swipe Task Completion Time

The results of the H-test indicate a significant group effect on swipe task completion time, $H(3) = 53.62$, $p = 1.35 \times 10^{-11}$. The post hoc Dunn-Bonferroni comparisons showed that the three haptic fidelity groups required significantly longer completion times compared to R. However, there were no significant differences found among the three VR conditions themselves. The results suggest that there exists an interaction overhead on the haptic fidelity groups, rather than haptic fidelity per se.

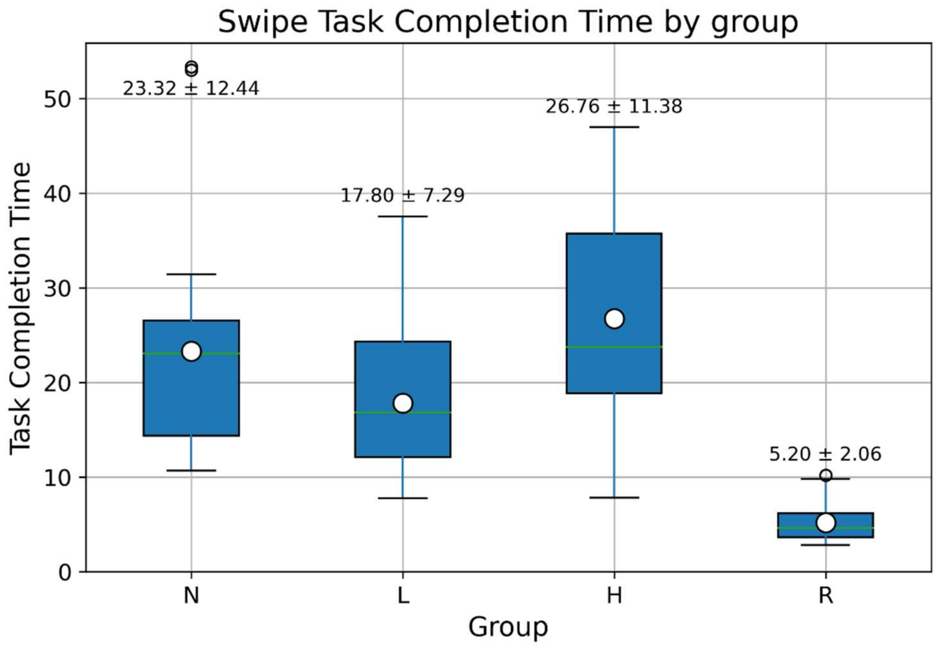

Figure 110 - Swipe Task Completion Time Box Plot

Table 23 - Dunn's Post Hoc Table on Swipe Task Completion Time

Comparison	p-Value	Significance
H vs L	0.293	Not Significant
H vs N	1.0	Not Significant
H vs R	$1.33{\times}10^{-10}$	Significant
L vs N	1.0	Not Significant
L vs R	$3.85{\times}10^{-6}$	Significant
N vs R	1.06×10^{-7}	Significant

Speed:

The assumption checks confirmed non-normal distributions across all groups, as demonstrated in the histogram and Q-Q plots. Meanwhile Levene's test verified homogeneity of variances. Therefore, a Kruskal-Wallis H-test is used to test the effect of groups on the swipe speed.

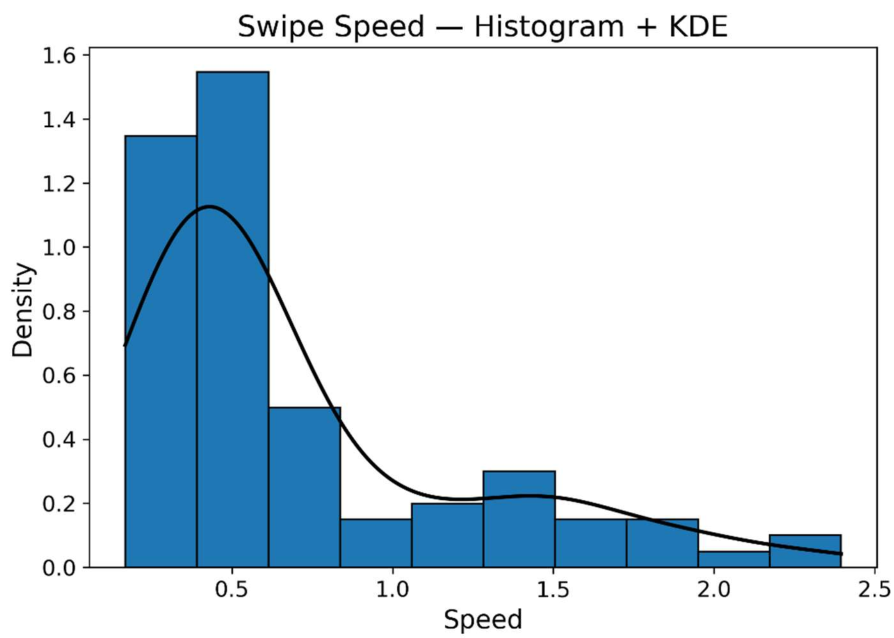

Figure 111 - Histogram + KDE of Swipe Speed

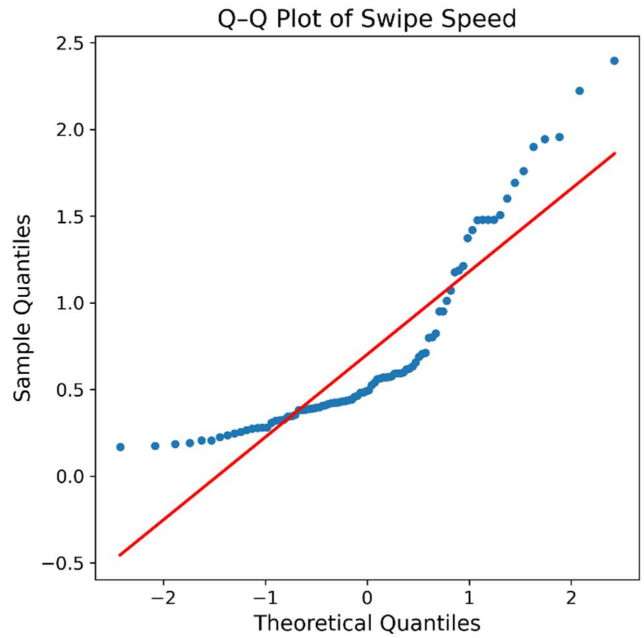

Figure 112 - Q-Q Plot of Swipe Speed

The results of Kruskal-Wallis H-test show that there is a significant effect of group on swipe speed, $H(3) = 53.03$, $p = 1.80 \times 10^{-11}$. Similar to task completion time, the real-world group (R) outperformed all of the three conditions in swipe speed, with no significant differences reported in between the three haptic fidelity groups. This suggests that haptic fidelity alone is not sufficient to achieve swipe speeds comparable to the real-world condition.

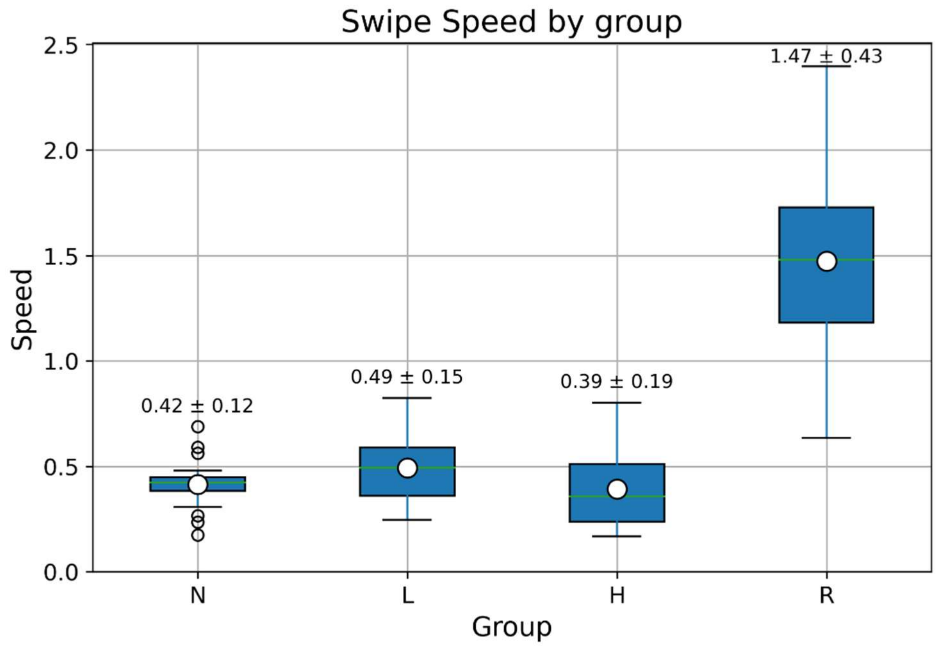

Figure 113 - Swipe Speed Box Plot

Table 24 - Dunn's Post Hoc Table on Swipe Speed

Comparison	p-Value	Significance
H vs L	0.506	Not Significant
H vs N	1.0	Not Significant
H vs R	4.09×10^{-10}	Significant
L vs N	1.0	Not Significant
L vs R	2.64×10^{-6}	Significant
N vs R	4.88×10^{-8}	Significant

4.3.5 Combinational Map Task

The combinational map task integrated multiple gesture types; it includes tapping through typing on a numeric keypad, panning through navigating through a map, pinching through resizing a shape, and swiping through navigating between a selection of emojis. This task combines discrete and continuous gestures, introducing higher cognitive and motor demands than an individual gesture task. Performance in this task was expected to depend on performance across all gestures.

Accuracy:

The assumption checks confirmed non-normal distributions in all groups. Levene's test showed homoscedasticity across groups. Consistent with prior tasks, the Kruskal-Wallis H-test was used for between-group comparisons.

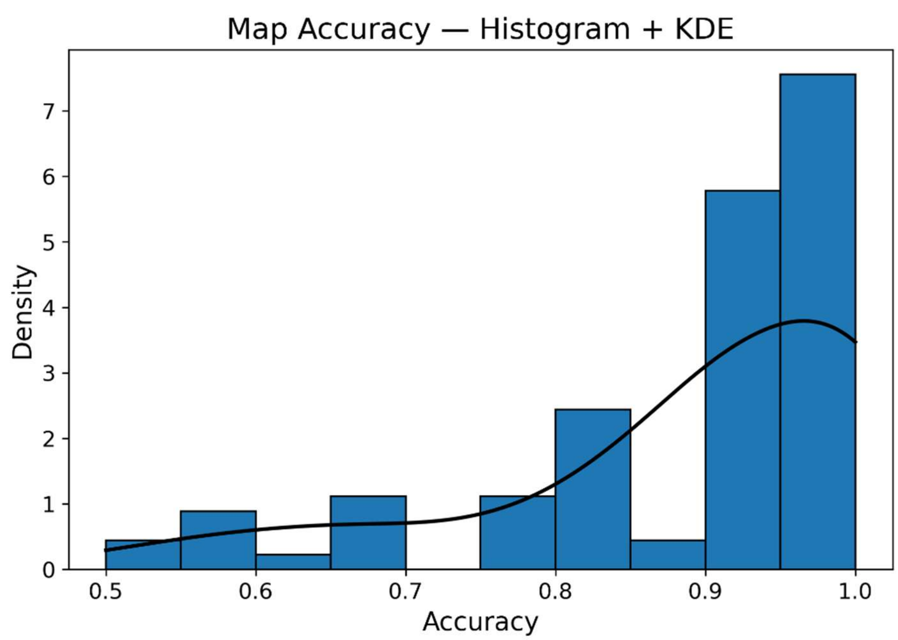

Figure 114 - Histogram + KDE of Map Accuracy

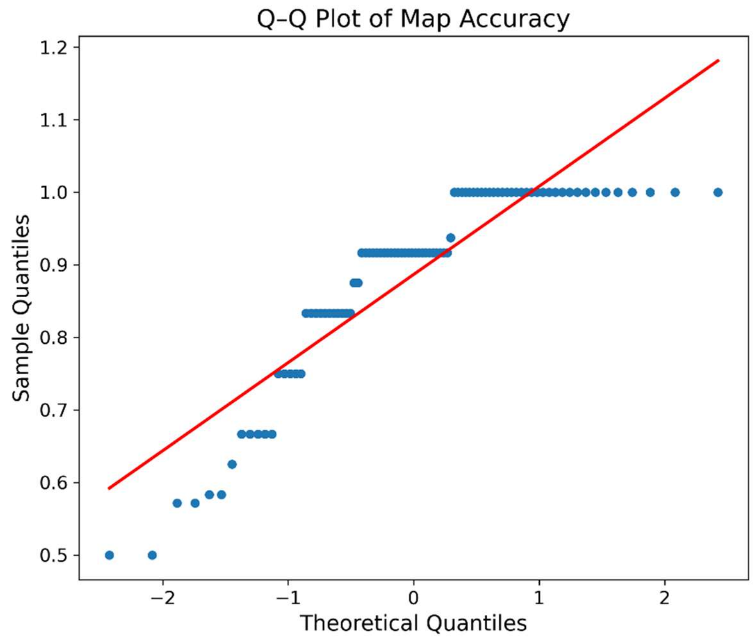

Figure 115 - Q-Q Plot of Map Accuracy

The results of the omnibus test show that there are no significant differences between groups in terms of accuracy, H (3) =1.21, p =0.750. Although the real-world group (R) showed a slightly higher mean (0.893), the four groups were statistically comparable. However, there was no direct impact of haptic feedback on improving the accuracy in the combinational map task. Based on the results of the omnibus test, no pairwise comparisons were made.

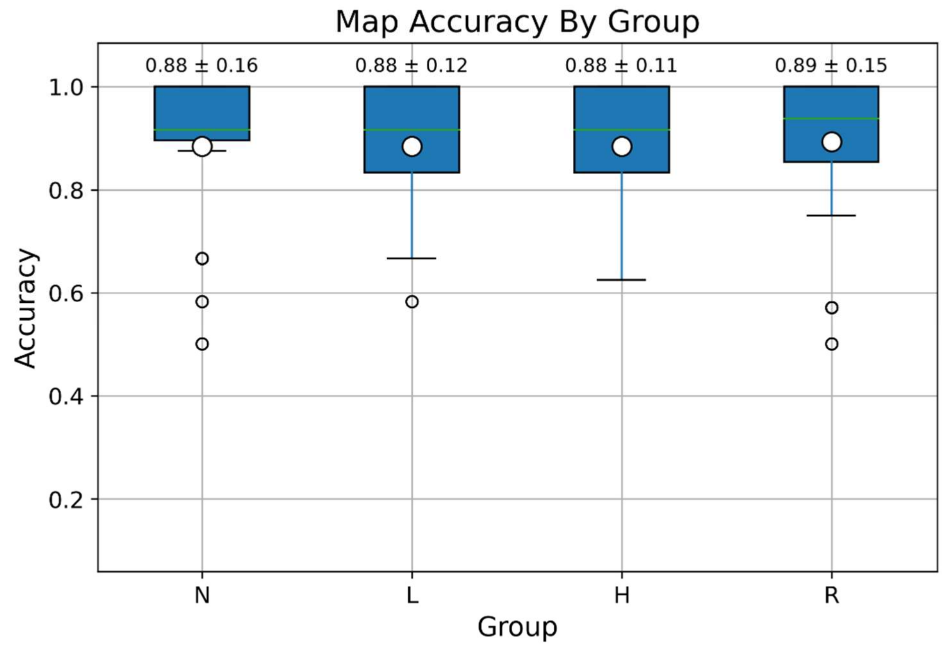

Figure 116 - Map Accuracy Box Plot

Error Rate:

The assumption checks indicate that the groups experienced non-normality, whilst the Levene's test show that the groups are homogeneous in variances. Similar to accuracy, the groups effect on error rate is evaluated using the Kruskal-Wallis H-test.

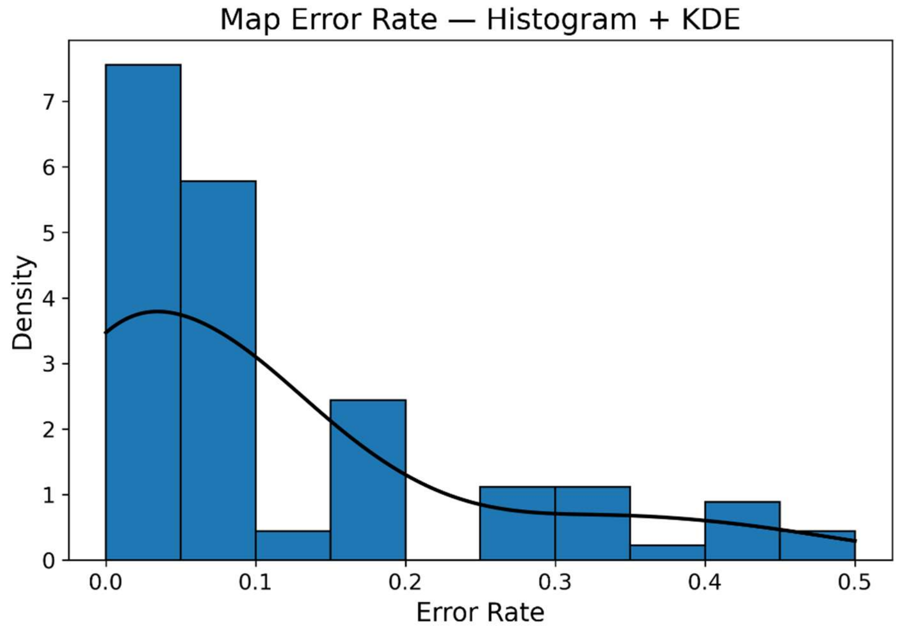

Figure 117 - Histogram + KDE of Map Error Rate

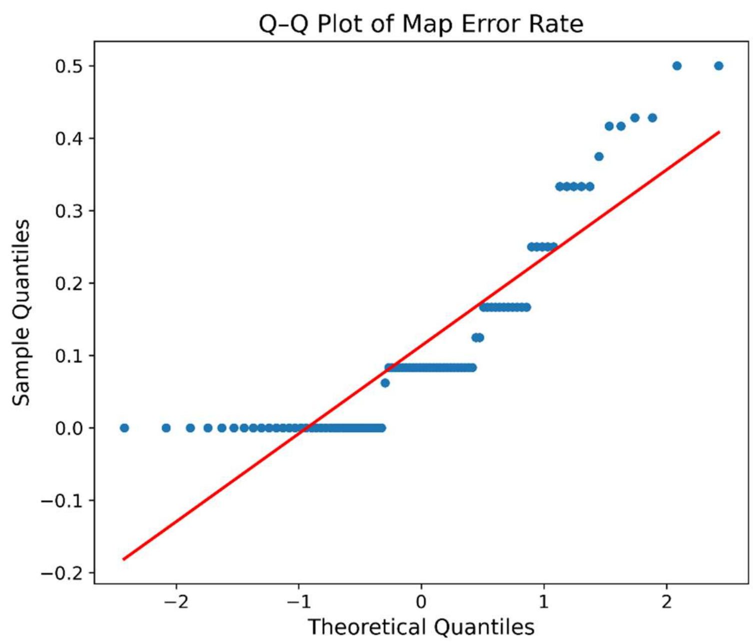

Figure 118 - Q-Q Plot of Map Error Rate

The Kruskal-Wallis test report that there are no significant differences among the groups in terms of error rate, H (3) = 1.211, p = 0.75. Therefore, there were no pairwise comparisons performed on the groups for error rate. Similar to accuracy, the increase in haptic fidelity did not translate to significant reduction in errors at the combinational task level.

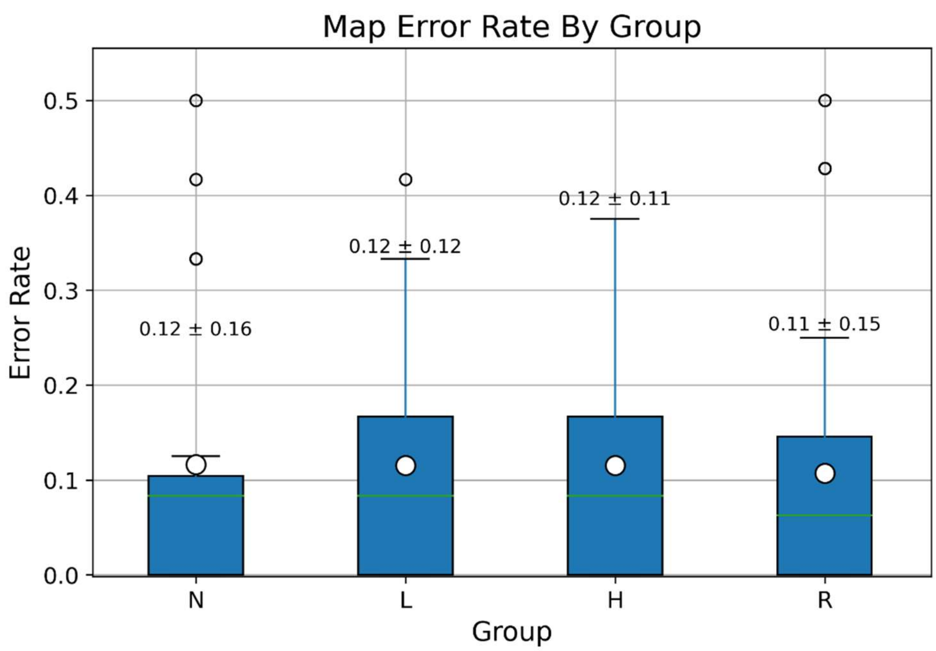

Figure 119 - Map Error Rate Box Plot

Task Completion Time:

The histogram and Q-Q plots show that the distributions were positively skewed with a long right tail. Shapiro-Wilk test indicated non-normality in the No Haptic feedback group, and Levene's test suggested unequal variances across the four groups. Therefore, the Kruskal-Wallis H-test was used for between-group comparisons.

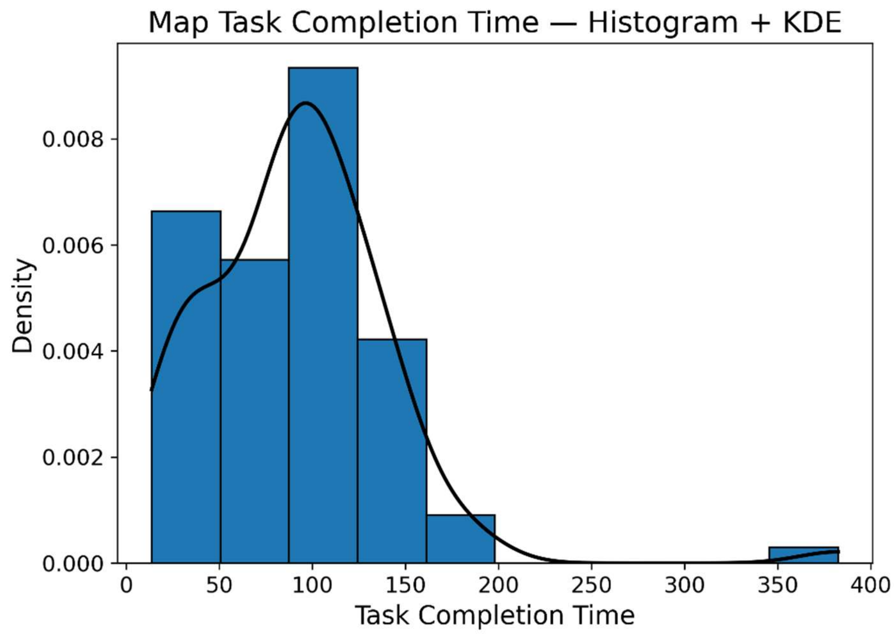

Figure 120 - Histogram + KDE of Map Task Completion Time

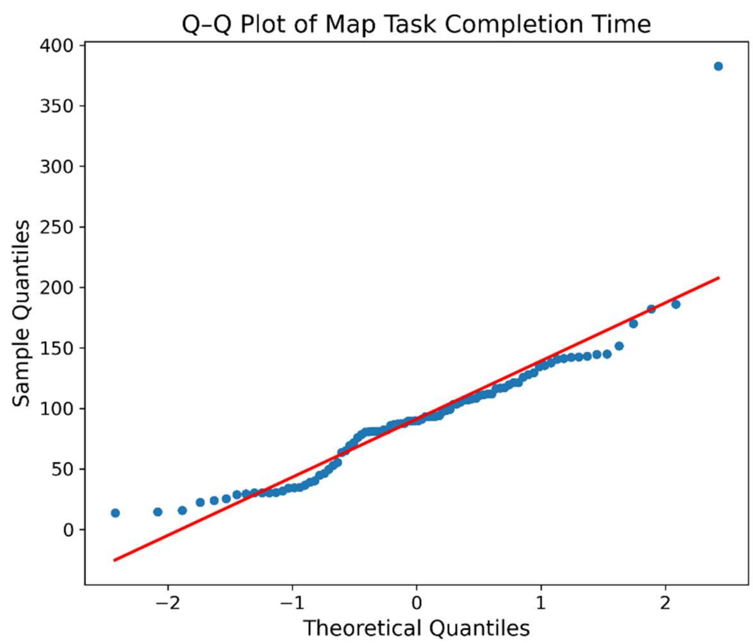

Figure 121 - Q-Q Plot of Map Task Completion Time

The omnibus test reported a significant difference between groups in terms of the task completion time, $H(3) = 50.89$, $p = 5.17 \times 10^{-11}$. The pairwise comparisons show that the real-world condition (R) was significantly faster than every haptic fidelity condition. Additionally, the pairwise differences among the haptic fidelity groups were not significant. This pattern suggests that the haptic fidelity alone does not improve task completion time.

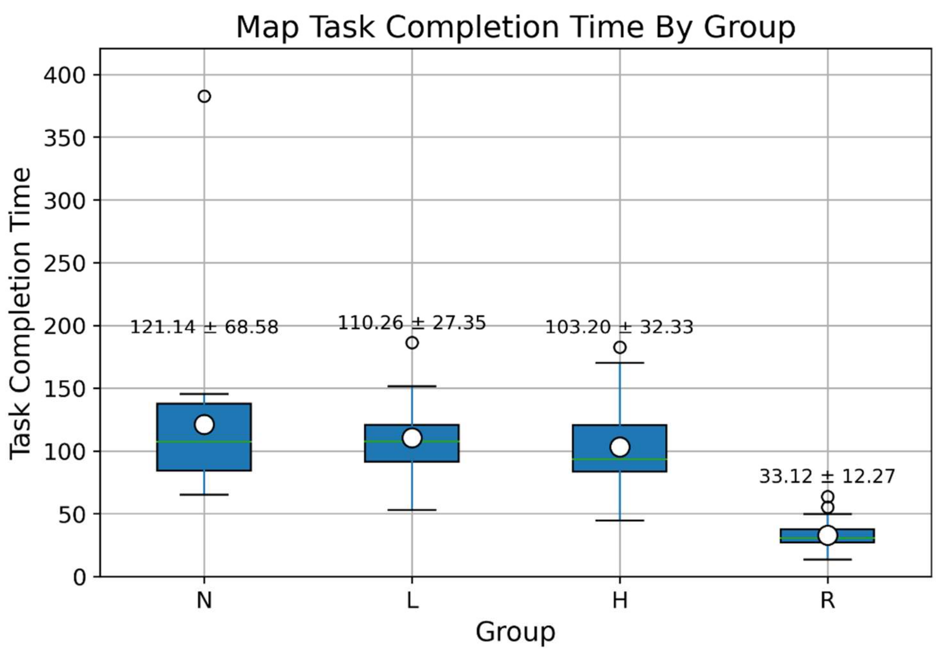

Figure 122 - Map Task Completion Time Box Plot

Table 25 - Dunn's Post Hoc Table on Map Task Completion Time

Comparison	p-Value	Significance
H vs L	1.0	Not Significant
H vs N	1.0	Not Significant
H vs R	1.23×10^{-6}	Significant
L vs N	1.0	Not Significant
L vs R	1.50×10^{-9}	Significant
N vs R	9.06×10^{-8}	Significant

Speed:

The Shapiro-Wilk test indicated that the speed was not normal in the high haptic fidelity group (H) and the other three groups showed normality. Moreover, the variances were unequal driven by the dispersion in real-world group relative to the haptic fidelity groups. The group effect on speed is tested using the Kruskal-Wallis H-test, in line with the analysis plan for non-normal and heteroscedastic data.

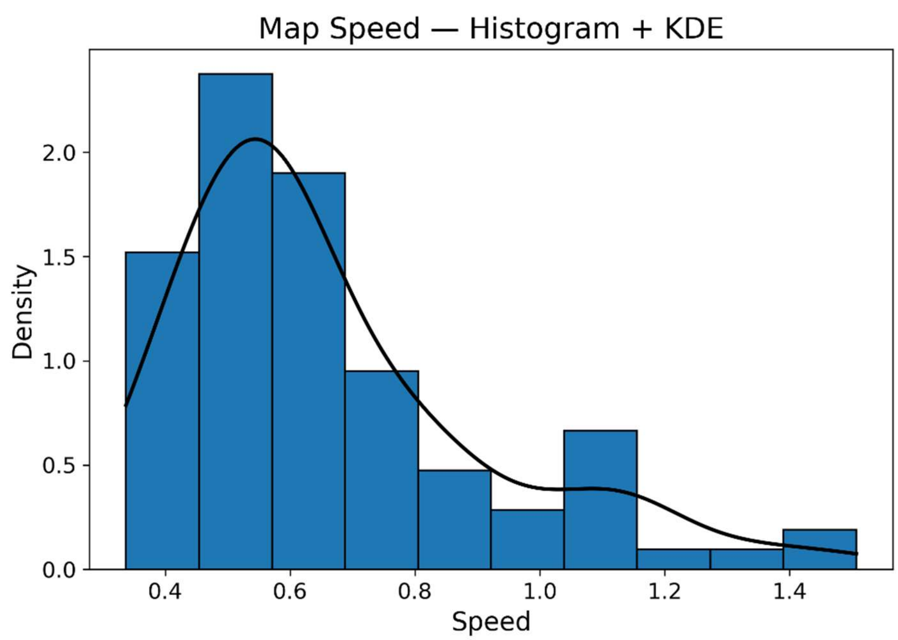

Figure 123 - Histogram + KDE of Map Speed

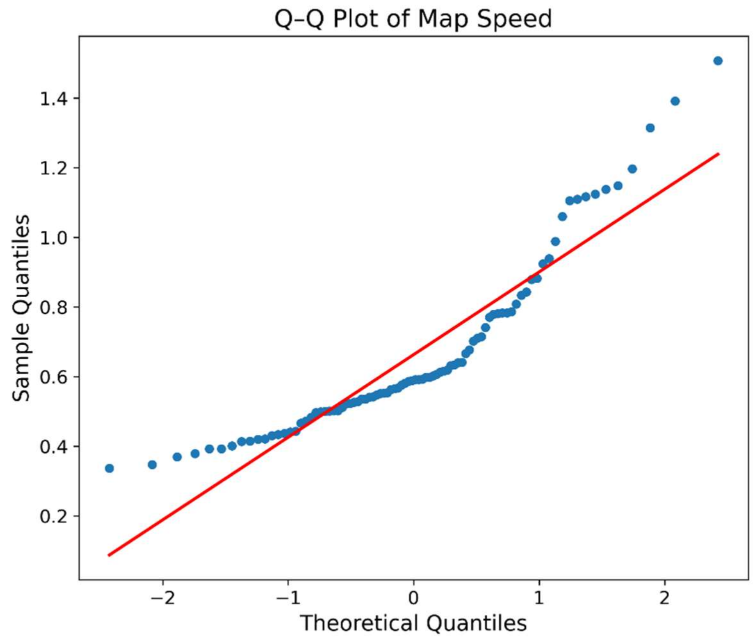

Figure 124 - Q-Q Plot of Map Speed

The omnibus test results report that there exists a significant difference between groups, H (3) = 35.65, p = 8.89×10^{-8}. The pairwise comparison of groups reported that the real-world group was significantly faster than the three haptic fidelity groups, and there are no significant differences reported between the haptic fidelity groups themselves. Similar to task completion time, haptic fidelity did not appear to have a direct effect on the speed at which users interact with the combinational map task.

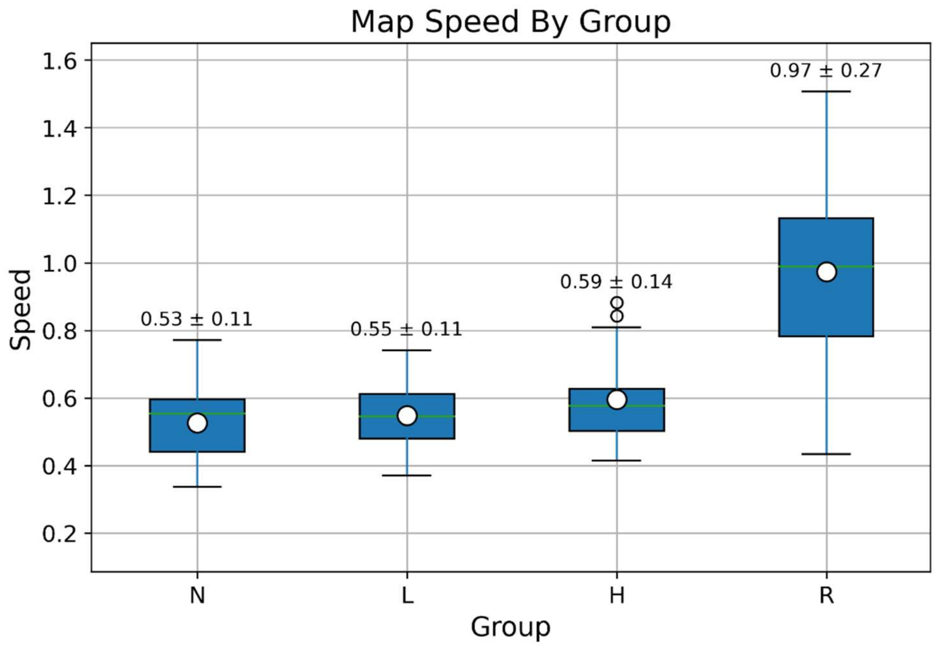

Figure 125 - Map Speed Box Plot

Table 26 - Dunn's Post Hoc Table on Map Speed

Comparison	p-Value	Significance
H vs L	1.0	Not Significant
H vs N	1.0	Not Significant
H vs R	2.28×10^{-4}	Significant
L vs N	1.0	Not Significant
L vs R	2.06×10^{-6}	Significant
N vs R	2.26×10^{-6}	Significant

CHAPTER FIVE

Discussion

This chapter explains the subjective and objectives results from chapter four and interprets them in a way tied to the study's research questions and prior work in HCI and haptics. This thesis examines how varying haptic fidelity, none (hand tracking only), low (vibrotactile), and high (combined tactile + force feedback) shaped participants' perceived presence, embodiment, and system usability, and how these conditions influence the accuracy, error rate, speed, and completion time across tap, pan, pinch, swipe, and the combinational map task. Additionally, the real-world touchscreen control is considered to reveal the external validity of the virtual touchscreen as well as the limitations of current virtual touchscreen interaction.

Three cross-cutting patterns make the discussion. First, the subjective experiences (presence, embodiment, and system usability) did not significantly differ among the three haptic fidelity conditions, suggesting that at the haptic fidelity level tested, visual and interaction consistency dominated perceived quality of the equipment. Secondly, the real-world condition consistently outperformed all VR conditions in terms of speed and task completion time, with major advantages in most tasks in terms of accuracy and error rates. Third, among the continuous gestures, the haptic high haptic fidelity narrowed the gap to real-world performance for pinch accuracy and error rate, whereas for pan and the combinational task showed no accuracy benefit from added haptics. On the other hand, discrete gestures such as tap showed no improvement from added haptic feedback. The patterns guide the following sections and inform the practical recommendations on when higher fidelity of haptics is warranted.

5.1 Overview & Synthesis

The results in chapter four can be understood through the three lenses that cut across measures and tasks:

1- What information each gesture actually needs from the haptic channel.

2- How consistently that information was delivered by the devices representing each fidelity band.

3- How much the end-to-end interaction pipeline added latency or uncertainty.

Based on these three lenses, the findings align with the haptic fidelity framework and the sensorimotor foundations laid out in chapters one and two, while directly answering the three research questions.

RQ1 – Subjective Experiences:

The subjective experiences were largely insensitive to variations in haptic fidelity. Presence, embodiment, and system usability showed no reliable differences and only small-negligible effects. A possible reason, consistent in the literature reviewed in chapter two, is that the dominant contributors to these constructs were visuomotor consistency (accurate hand tracking and stable control-display mapping) and the factors of scene coherence (shared across haptic fidelity conditions) rather than the incremental of the tactile and kinesthetic cues introduced by the three groups. Once the visual fidelity and consistency of interactions appear to be above a threshold, the marginal differences in haptics do not strongly shift the perceived metrics.

RQ2 – Objective Performance and The Real-World Baseline:

Throughout the five tasks, the physical touchscreen provided advantages in speed and completion time, and often in accuracy and error rate, which underscores the external validity gap that remains between virtual and physical touch today. Such advantage is expected; the real device affords instantaneous cutaneous contact, better frictional coupling, and zero actuation delay. Additionally, the real-world group has the ability to use the full suite of mechanoreceptors and proprioceptive cues. Even with the high-fidelity gloves, the VR pipeline introduces small latencies, noise from tracking. Since the high-fidelity gloves are multimodal, actuation complexity adds to the slow continuous motions. Therefore, the haptic fidelity conditions were reliably slower in all of the five tasks, even when their accuracy approached the real-world benchmark.

RQ3 – Gesture Specific Sensitivity to Haptic Fidelity:

The performance data reveals clearer separations, anchored by the real-world baseline. For tap, the physical tablet touchscreen yields ceiling level accuracy, zero errors, and faster task completion time and speed from all haptic fidelity conditions; within the haptic fidelity conditions, the incremental in haptic fidelity does not significantly differentiate performance on this discrete target selection gesture. Similarly for pan, the accuracy was uniformly high across the conditions, but the real-world group produces significantly faster times and higher speeds, which could point out a possible residual latency and constraints of VR regardless of the haptic fidelity.

Pinch reveals where higher fidelity matters. The real-world group still dominates completion time and speed, yet the high haptic fidelity glove is the only haptic fidelity condition whose pinch accuracy and error rate are not statistically different from the real-world group. Meanwhile the no haptic fidelity and low haptic fidelity groups lag behind in these measures. Even so, the haptic fidelity conditions did not significantly differ from each other on the pinch task completion time and speed, which suggest that the increase in the haptic fidelity level narrows the gap of accuracy and error rates for bimanual scaling rather than eliminating the costs in throughput.

Swipe behaves like a hybrid. The accuracy is comparable across all conditions, but the error rates are lower in the real-world group than in the no haptic feedback group. Thus, adding either haptics (whether low or high) brings error rates to be aligned with the real-world baseline. However, for the speed and task completion times, remain better in the physical setting than in any haptic fidelity condition, which suggests that the motion efficiency is constrained by factors beyond haptic fidelity alone.

The combinational map task, which ties the separate four gestures together, shows comparable accuracy and error rates across the four conditions, yet the real-world condition completes the task faster and moves quicker overall. Among the haptic fidelity conditions, pairwise differences are not significant, which reassures the idea that haptics does not by itself reduce interaction overheads introduced by using VR.

In summary, the results provide a practical boundary. If the intention of the use is to maximize throughput on discrete or continuous gestures, a physical touchscreen still sets the bar. If the goal is to preserve precision for gestures that rely on contact cues, high fidelity haptics can close accuracy and error rate gaps relative to reality. Conversely, for perceived metrics like presence, embodiment, and usability, simply adding haptics does not guarantee noticeable gains over hand-tracking alone.

5.2 Interpreting Subjective Outcomes

Presence, both as a total construct and through spatial presence, involvement, and experienced realism, was statistically indistinguishable across the haptic fidelity conditions. Given the near-normal distributions and acceptable variance for the total score, the small non-significant ANOVA effect indicates that the increase in haptic fidelity did not translate to higher sense of presence. This due to practically, two reasons:

1- **Ceiling effect from strong visuals and tracking:** The XR-3 high visual fidelity and hand tracking provide a strong baseline for presence.

2- Task ecology: the interaction context was a virtual tablet on a static table inside VR. Which makes screen-centric work may emphasize visuomotor alignment over object-centric haptics, reducing the influence of richer haptic cues on presence ratings.

The subscales reinforce the idea, even with spatial presence and experienced realism violated normality, but remained non-significant in Kruskal-Wallis tests; Involvement passed the assumption checks yet was non-significant in ANOVA. Combined together, these patterns imply that the sensory congruence was already good enough that additional haptic feedback did not shift presence outcomes.

Embodiment totals (Ownership, Agency, Change) did not differ by the haptic fidelity condition. This suggest that the visual-motor congruence and the stability of the hand tracking were sufficient to support agency and ownership over the avatar hands. The timing match between participants' movements and the virtual hand response likely dominated the embodiment appraisal, and the tactile and kinesthetic feel did not add enough incremental evidence to move the overall embodiment score.

The system usability analysis echoed presence and embodiment, with no significant differences. Although the data contained an interesting ranking of Low Haptics > High Haptics > No Haptics. This could possibly be due to two reasons:

1- **Usability vs. realism trade-offs:** Low fidelity gloves are lighter and less restrictive than high haptic fidelity gloves, which can improve the ease and comfort, even if the high haptic fidelity gloves provider richer feedback.

2- **Uniform interaction model:** All of the haptic groups used the same UI, task flow, and tracking. This provides why the learnability and consistency were comparable. Therefore, system usability differences favored low haptics, even if not significant. Importantly, all groups showed means > 60 which indicates acceptable usability for all haptic fidelity conditions.

5.3 Interpreting Objective Outcomes

In line with RQ2 and RQ3, this thesis contains the interpretation of the objective results by asking what each gesture needs from the haptic channel, how reliably the information was delivered by each fidelity level, and how latency in the VR pipeline shaped throughput. Across the five tasks, the real-world set a clear benchmark for speed and completion time; the haptic fidelity conditions sometimes matched accuracy but never matched throughput. Where the haptic channel conveyed task-critical contact and resistance cues (pinch, swipe), fidelity mattered; where visual targeting sufficed (tap), or where continuous motion was constrained possibly by pipeline latency (pan), added haptics did not narrow the gap to reality.

5.3.1 Discrete Gestures

The tap gesture reached ceiling-level accuracy and zero errors on the physical touchscreen, with significantly faster speeds and shorter completion times than the haptic fidelity conditions. Within the haptic fidelity groups, increasing the fidelity level did not differentiate accuracy, error rate or even throughput (speed and task completion time). Which is suggesting for a discrete, visually guided "point and commit" action, haptic cues beyond a good and stable visual mapping add little marginal value at the levels tested. The possible performance limiters in haptic fidelity groups were end-to-end latency and small tracking noise that complicate high-confidence target confirmation, not the absence of the haptic cues themselves. However, there is a necessity for empirical grounding for these possible factors. In practice, for tap-heavy interfaces, investing in higher haptic fidelity is unlikely to buy measurable performance gains unless it simultaneously reduces the delay in the pipeline or improves the stability of targeting.

Meanwhile for swipe, accuracy was comparable across the four groups. However, the real-world condition yielded in lower error rates than the no haptic fidelity group; adding low haptic feedback or high haptic feedback reduced the error rates to align with the real-world condition, even though speed and task completion time still favored the real-world condition. The swipe gesture benefits from a sense of surface contact ("you're on the surface and moving" cue) to avoid under/over swipes, which the low and high haptic feedback groups can provide. But the speed of the gesture and time to complete the task remained bounded by VR latencies. For content browsing and page turns, low-cost vibrotactile gloves may be sufficient to stabilize error rates. However, incrementing the fidelity level by itself will not translate to better speed.

5.3.2 Continuous Gestures

For the pan task, accuracy and error rates were uniformly high across all conditions, but the real-world group was reliably faster with higher pan speeds than every haptic fidelity condition. Additionally, no pairwise differences emerged among the haptic fidelity conditions themselves. In pan, continuous motion is limited by the interaction pipeline, even small VR delays nudge users toward more conservative, corrective trajectories. The increment in haptic fidelity level did not result in smoother or faster motion, likely because the pan gesture relies on temporal predictability and visual path control than on the cutaneous detail. For slider and drag dominant UIs, possible gains might come from lowering the end-to-end latency and improving the smoothness of the motion rather than increasing the haptic fidelity level.

Meanwhile for pinch, is where fidelity mattered. While the real-world group dominated the speed and task completion time measures, but the high haptic fidelity group was the only haptic fidelity condition whose pinch accuracy and error rate were statistically similar to the real-world condition; the no haptic fidelity and low haptic fidelity groups lagged behind on these metrics. The bi-manual scaling depends on the contact localization, normal force cues, and resistive feedback to calibrate how much to pinch/stretch, which the high haptic fidelity gloves uniquely approximated via combined tactile and kinesthetic cues. However, the speed and time taken to complete the task remained limited by the latencies and delays and the coordination cost of two fingers. In practice, if the workflow demands precise on-screen scaling, high haptic fidelity gloves can recover the real-world like accuracy and error rates, even if interactions remain slower overall.

5.3.3 Combinational Map task

The combinational map task is a compound task that chained typing (tap), alignment (pan/pinch), and browsing (swipe). The accuracy and error rate of the overall task were statistically comparable across all four conditions, yet real-world group finished faster and at higher overall interaction speeds. Additionally, no differences appeared among the haptic fidelity groups themselves. Two reasons likely explain this trend:

1- **Additive Overheads:** The task inherits the slowest elements of its parts, VR's possible latency bottleneck, and the costs of actuation and coordination, which automatically inflates the time taken even when accuracy is preserved.

2- **Mode Switching Costs:** The switch between discrete and continuous gestures amplifies any timing jitter or friction in the VR pipeline; the high haptic fidelity alone does not remove these costs.

In operation modes, in multi-step UIs that mix gesture types, designers should expect accuracy to generalize well across any VR configuration but should expect extra time to complete the task unless the pipeline delays are tackled.

5.4 Practical Implications & Design Guidelines

The results suggest a simple and actionable rule: match the haptic fidelity level of the system to the information a gesture actually needs, and spend the rest of the budget on improvement of tracking stability, while keeping the devices comfortable. Since the subjective outcomes were largely insensitive to the presented fidelity manipulations, implying that once the visuomotor consistency is high, adding richer sense of touch alone does note change the user-reported experience. Practically, the investments should therefore prioritize tracking quality, the coherence of the scene, the stability of the interactions before upgrading the haptic hardware.

For a tap heavy application (keypads, soft buttons, and confirmation dialogs), the priority goes to crisp visual targets, precise hand tracking, low clicking latency, and generous hit regions over haptic fidelity upgrades. If cue is desirable, a confirmation buzz is sufficient as it will act as feedback rather than guidance. This keeps the gloves light and reduces the overhead complexity without sacrificing objective performance.

For “state-change” gestures that involve clear transition (view switch/page turn), any form of haptics helped stabilize behavior relative to no haptics. Vibrotactile would be a confirmatory cue for the transition itself, while throughput depends more on the latency of the pipeline. In practice, the design should contain a short well-timed pulse at the state boundaries and provide more effort on latency reduction.

For continuous path-following (pan/slider control), the implication is to tune the interaction loop, not the glove. This would be possible by smoothening micro-jitters in hand tracking; use velocity-scheduling to preserve fine control near targets; and provide strong visual affordances that help the user predict the motion.

For continuous bimanual scaling (pinch), the haptic fidelity mattered for narrowing the error rate and accuracy scores to the real-world touchscreen. When the task requires fine, symmetric force modulation, high haptic fidelity gloves are justified to recover the real-world precision even though the speed will remain bounded by the pipeline. When implementing a bimanual scaling heavy system, the study recommends the use bias actuation to contact onset/offset and small differential changes where the perceptual benefit is largest as well as providing clear visual thresholds so users can confirm their satisfaction without over-correcting.

For mixed workflows, designers should reduce the mode-switch friction: provide clear transaction boundaries (using visuals and vibrotactile ticks) so users can commit and move on without hesitation. If the completion time matters more than peak accuracies on any single gesture, prioritize latency work and interaction flow over the quality of haptics.

Finally, because the user-reported perceived metrics did not separate reliably across haptic fidelity levels in our data, future implementers should not expect haptics alone to “buy” better perceived experience once the visuals and tracking are strong. If usability is priority, favor lighter, less restrictive gloves and fast setup over increasing the complexity of systems, unless the task demands the needs of haptic realism for precision (as with pinch).

5.5 Limitations

While the study was designed to isolate the effect of haptic fidelity on gesture-based touchscreen interaction, several limitations should be considered when interpreting the findings and when planning follow-on work. The following sub-sections explain the limitations in further detail.

Sample Size and Comparison:

The priori analysis targeted N = 128 (32 per group), the analyses performed here were concluded on the subset of participants tested at the time of the writing. This causes a reduction in sensitivity to small effects and increases the chance of both Type II (missed effects) and unstable effect-size estimates. Additionally, the convenience sample skewed toward young, right-handed participants with limited prior experience using VR gloves. The generalization to older adults, left-handed users, expert operators, or clinical populations should be made with caution.

Between-Subjects Design:

The between-subjects approach was chosen to minimize carry-over and fatigue. However, it is inherently less sensitive than a within-subjects design to detect differences among the haptic fidelity conditions. The variability in motor control, learning rate, and VR comfort can inflate error terms and hide small but meaningful fidelity effects.

Calibration and Personalization:

Although multiple haptic feedback glove sizes were provided depending on the hand size of the user, as well as the high degree of freedom for calibration and adjustment of the HMD. The participants differ in skin sensitivity, hand size, and glove fit could have dampened the perceived haptic feedback quality.

Seated Usage:

All conditions were performed seated in a controlled lab. The stabilization of the posture reduced the gross arm movement and limit the generalization to standing, walking, or collaborative scenarios where proprioceptive cues interact more strongly with haptics.

Software and Hardware Limitations:

The VR environment (Unreal Engine 4.27), the HMD (Varjo XR-3), and the chosen haptic gloves define a high-end, research grade stack. Results may differ on commodity HMD, different tracking systems, or more stable glove firmware. Similarly, the real-world benchmark tablet touchscreen (Microsoft Surface Pro 4, Operating system stack) may not represent all physical touchscreens.

5.6 Future Work

Building on this study's comparative evaluation of the impact of haptic fidelity on gesture-based touchscreen interactions, the next steps should pursue two coupled trajectories: engineering work that reduces the persistent throughput gap between virtual and physical touch, and statistical analysis on the completed sample and richer interpretation to clarify how subjective experience and performance co-vary. Both approaches are feasible within the apparatus, tasks, and logging pipeline already in place.

There is a necessary need for an upgraded gesture translator for VR, that is explicitly contact-aware and stateful. In the current implementation, gesture detection is primarily kinematic: taps, swipes, pans, and pinches are inferred from finger trajectories and distances with task-level thresholds. This works well enough to recover accuracy for simple targets but is vulnerable to small tracking jitter and temporal uncertainty, which our results suggest manifest as slower execution and occasional state-transition errors. A next generation gesture translator would fuse multiple signals, such as finger pose and velocity, inter-digit distance and its derivative, palm orientation, micro-pauses. It is believed that one can combine a state machine with a classifier model (e.g. Recurrent Neural Networks – RNN) trained the already captured event and time-based logs to predict state transitions in real time.

A second priority is to measure and minimize the end-to-end latency components that lag the motion efficiency in VR. The results from chapter four show a consistent speed and completion time advantage for the real-world group across all tasks, even when haptic fidelity conditions' accuracy approaches the physical baseline. The future iterations of this study should instrument the pipeline with time stamps for tracker sample acquisition, gesture translator state changes, and the components of the haptic feedback interaction, if present.

Moreover, completing the recruitment to the planned sample size and then re-analyzing with full sample will support correlational questions between the independent variables that are currently under-powered. With 128 participants across four conditions, the study will be able to detect small-to-moderate associations between the subjective and objective independent variables, both overall and within a gesture specific nature. Additionally, since the logs include event-level timing information, it is possible to derive micro-kinematic features like pause counts, jerk, and overshoot distance. The derivation of micro-kinematic movements will allow further investigation of the haptic fidelity and the outcomes in a task.

CHAPTER SIX

Conclusion

This thesis is set out to clarify when and for what kinds of touchscreen gestures haptic fidelity meaningfully improves the experience and performance of the interaction in immersive environments. Established in the anatomy of touch and the haptic fidelity literature, the work framed haptics not as a monolith but as a channel whose utility depends on the task's information needs, on the reliability, and latency of the surrounding pipeline. The contribution highlights the gesture-sensitive account of haptic value; where higher haptic fidelity pays off, where lower cost cues suffice, and where neither overcomes the real-world baseline.

Methodologically, the study used a between-subjects design across four conditions: no haptic fidelity (hand tracking only), low haptic fidelity (vibrotactile gloves), high haptic fidelity (tactile + kinesthetic feedback), and a real-world touchscreen control. These conditions were tested across five tasks: tap, pan, swipe, pan, pinch, and a combinational map task. Subjective outcomes (presence, embodiment, system usability) were collected with validated instruments (IPQ, VEQ, SUS), and objective outcomes (accuracy, error rate, speed, task completion time) that were logged per task. The alignment of the measures against the same interaction set enabled clear attribution of effects to gesture demands and to the information actually delivered by each fidelity band.

With respect to RQ1, the perceived experience proved largely insensitive to the increments of haptic fidelity tested. Presence (includes spatial presence, involvement, and experienced realism), embodiment (includes ownership, agency, change), and system usability did not differ among the three haptic fidelity conditions. A possible plausible explanation, consistent with the outcomes of the background and literature, is that high quality visuals, stable hand tracking, and consistent control mapping established a satisfactory baseline for these constructs. Therefore, visual and interaction coherence dominated perceived quality in the screen-centric context.

For RQ2, the real-world condition remained as the benchmark for throughput, as it was consistently faster and time efficient than all haptic fidelity conditions, even when haptic fidelity conditions approached the real-world values. Such pattern exposes two points; (i) instantaneous cutaneous contact, frictional coupling, and the mechanoreceptive and proprioceptive cues directly influences the speed of the interaction, (ii) VR overheads like tracking jitter and actuation delays accumulate into slower continuous motion and end-to-end task completion times.

RQ3 shows where haptic fidelity level matters most. Discrete, visually targeted selection (tap) showed no measurable gains from adding haptic feedback, this is due to the ceilinged accuracies and error rates that matched real-world group, and the haptic fidelity conditions only differed in speeds and completion times from the benchmark condition. Swipe had blended results, adding low or high haptic fidelity devices aligned error rates with the real-world baseline (relative to no-haptics condition) but it did not reduce the speed deficits. In Pan, a path-following motion influenced by visual guidance and predictability, showed uniformly high accuracy across all four conditions and the same speed gap in comparison to the real-world condition. Pinch, by contrast, showed clear advantage for the high haptic fidelity. The high haptic fidelity condition is the only condition that managed to narrow down the accuracy and error rate gaps relative to the real-world condition, even though the haptic fidelity groups remained slower.

In theory, these findings go hand-in-hand with the haptic fidelity framework by linking device compatibilities to the gesture information needs. Haptics seem to function effectively as a confirmation cue for discrete changes, but its stronger contribution when the task demands more continuous perception of contact distribution like in pinch scaling. On the other hand, when the objective of control is to track a visible path under stable mapping, additional skin-level detail aids in guiding what vision and proprioception already provide.

In practice, this work offers guidance for VR/AR design and procurement. If the desired goal is to maximize throughput on common screen interactions, real-world settings still set the bar. When accuracy on bimanual scaling is critical, high haptic fidelity gloves can recover real-world accuracy while accepting slower overall pace. For swipe heavy interfaces, economically the low haptic fidelity vibrotactile cues may be sufficient to stabilize error rates. For pan and tap heavy workflows, investments in reducing latency and improvement of tracking stability are likely going to yield in larger gains than the addition of haptic feedback.

As with any empirical effort, limitations affect interpretations. Results reflect the devices, software stack, and the tasks implemented (e.g. VR hardware, gloves from factors, Unreal Engine 4.27 project architecture and associated SDK constraints), and the generalization to other devices or interaction ecologies should be made cautiously. The choice of between-subjects design avoided learning effects but necessarily trades the within-participant sensitivity for ecological realism. The future work completing the planned sample size would support finer-grained correlation analyses across subjective and objective measures. Even so, the present patterns are internally consistent and align with the sensorimotor rationale motivating the study.

In closing, this thesis sends a clear message, that is empirically supported, that haptic fidelity is not a blanket cure for the performance and experience gaps between virtual and physical touchscreen interfaces. Therefore, it provides the path to more effective immersive touch interfaces by deploying higher haptic fidelity devices where the task can exploit it, and in parallel, continue the efforts toward reducing end-to-end latency and improve consistency so that the haptic fidelity has room to matter.

APPENDIX A

IRB APPROVAL LETTERS

OAKLAND UNIVERSITY

Institutional Review Board

Date: October 24, 2024

Study #: IRB-FY2025-56

Study Title: Evaluating Haptic Experience in Virtual Reality

Submission Type: Initial IRB Decision: Approved

Research Team:
Abed AlJundi
Osamah Rawashdeh, Wing-Yue Louie
Absalat Getachew, Andrea Macklem-Zabel, Solaf Athamnah, Fares Al-Shubeilat

Based on applicable federal regulations, the above referenced study has been determined to involve no more than minimal risk to participants and to be Approved, with the following expedited categories: 6. Collection of data from voice, video, digital, or image recordings made for research purposes.
7. Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies. (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(2) and (b)(3). This listing refers only to research that is not exempt.)

This approval is based on an appropriate risk/benefit ratio and a project design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

Notes for Researcher(s):
This submission includes the following approved documents

- Registration form
- Flyer
- Recruitment Email
- Date Stamp Approved Consent Form v 10/24/24

Letter and Consent Document:
This letter along with the IRB approved (date-stamped) consent document can be found in Cayuse in the Submission Details page under Letters and Attachments, respectively.

The IRB approved version of the consent document must be used in consenting participants. Federal regulations require that each participant receive a copy of the consent document unless a waiver is granted by the IRB. Signed consent forms must be retained for a minimum of three years after the completion of the project. Please remember that informed consent is a process that continues throughout the project, starting with recruitment and assurance of participant understanding of the project, and followed by a signed consent form when applicable.

Permission from Research Sites: Please note the following:

- This IRB approval letter means that the research has met the federal criteria for approval per 45 CFR 46.111 Criteria for IRB Approval of Research.
- Before the research is initiated, permission to conduct research at a given site must be obtained from all research locations listed in the IRB submission. You must keep copies of all such permission letters for your records.
- It is the responsibility of each researcher to follow all applicable policies and procedures of any outside institution where the research will be conducted.

Modifications:
Any changes to the approved project must be approved by the IRB prior to initiation by submitting a MODIFICATION request. Do not collect data while the changes are being reviewed. Data collected during this time cannot be used in research.

Incidents:
All unanticipated problems involving risks to participants or others, serious and unexpected adverse events, non-compliance issues and/or serious complaints regarding this project must be reported promptly to the IRB by submitting an INCIDENT report.

You are approved to start the research. Please retain a copy of this notification for your records.

If you have any questions, please contact the IRB office.

Thank you.

The Oakland University IRB

OAKLAND UNIVERSITY

Institutional Review Board

Date: November 7, 2024
Study #: IRB-FY2025-56
Study Title: Evaluating Haptic Experience in Virtual Reality
Submission Type: Modification
IRB Decision: Approved

Research Team:
Abed AlJundi
Osamah Rawashdeh, Wing-Yue Louie
Absalat Getachew, Andrea Macklem-Zabel, Solaf Athamnah, Fares Al-Shubeilat
The IRB has reviewed the Modification submission for the above referenced study. The modified study with the changes listed below has been determined to involve no more than minimal risk to participants and is Approved through an expedited review per federal regulations.
The approved modifications are the following:

- Addition of new potential risks (VR sickness and skin irritation)
- Revision to compensation procedure (now providing full compensation for participants who must discontinue due to VR sickness or skin irritation)

This submission includes the following revised document:

- Date Stamp Approved Consent Form_version 11.07.24

The IRB approved (date-stamped) consent document(s) has been published under Attachments in the Submission Details page. Please make sure to use the most recent IRB approved version of the consent form in consenting participants.
You are approved to implement the aforementioned modifications. Please retain a copy of this notification for your records.
This letter can also be found in Cayuse under the Letters tab in the Submission Details page.
If you have any questions, please contact the IRB office.
Thank you.
The Oakland University IRB

APPENDIX B

GVSC OPSEC REVIEW STATEMENT

APPENDIX C

FORMS, QUESTIONNAIRES, AND SURVEYS USED

Consent Form
Evaluating Haptic Experience in Virtual Reality

Introduction

You are being asked to participate in a research study that is being conducted by Abdel Rahman Aljundi, Fares Al-Shubeilat, and Solaf Athamnah under the direction of Dr. Osamah Rawashdeh, Professor & Chair in Electrical and Computer Engineering Department and Dr. Wing-Yue Geoffrey Louie, Assistant Professor in the Electrical and Computer Engineering Department.

Your decision to participate in this study is voluntary. You can choose to stop your participation at any time if you are not comfortable. Your decision will not affect your present or future relationship with Oakland University, the researcher, or the Electrical and Computer Engineering Department.

If you are a student or employee at Oakland University, your decision about participation will not affect your grades and/or employment status.

What is the purpose of this study?

Interactions within virtual environments are enhanced by haptic feedback. The primary purpose of this study is to find out how different haptic fidelity Levels influence the user's haptic experience, interactions, and performance across various tasks and environments.

This understanding will help inform the design of future virtual reality (VR) systems to ensure they are both effective and immersive for users.

Who can participate in this study?

You are being asked to participate in the study because

- You are between 18-64 years old.
- You speak the English language fluently.

You will **NOT** be asked to participate in the study if you meet any of the following criteria or possess any of the following conditions/ailments:

- Are under 18 or over 64 years old.

- Do not speak English.
- Need corrective glasses.
- Have any physical condition that could affect your ability to perform tasks involving the use of your arms or hands.
- Have epilepsy, a history of seizures, migraines, or recent history of motion sickness.
- Generally feel uncomfortable with simulated motion or VR experiences
- Have a contagious disease, including but not limited to skin, scalp, or hair conditions.
- Are pregnant.
- Have difficulty sitting for extended periods of time while wearing a VR headset.

How long will I be in the study?

You will participate in one session which will take an hour on average to complete, each session contains two experiments.

Where will this study take place?

This study will take place at Oakland University, Rochester, MI.

What do I have to do?

Based on your group you will be asked to do some of the following:

> You will spend some time at the beginning to understand the setup and learn how to put on the necessary gear if needed for your group setting (10 minutes). After that you will go through a tutorial run (10 minutes). You will then complete a series of tasks (15 minutes). Following the tasks, you will out questionnaires (10 minutes). Once you have completed the final questionnaire, you will participate in an interview with Cooper (10 minutes). In total, the study will take around one hour to complete.

Are there any risks to me?

If your group assignment includes a VR headset, it is possible to accidentally fall when interacting with the virtual environment, this risk is minimized as you will be seated on a chair throughout the experiment. Additionally, there will be plenty of free space in front of you to allow for free movements without obstacles. The researcher will also provide instructions on safe use and monitor your activity to further reduce any potential risks.

There is a rare risk of irritation caused by wearing the headset or gloves. You will undergo a trial session, and if you experience any symptoms or discomfort, the study will be stopped for you.

You may experience symptoms of Virtual Reality Sickness, such as dizziness or discomfort. Participants with any history of these ailments are excluded from the study. After the trial session, you will fill out a virtual reality sickness survey. If you report any symptoms or indicate that you're not feeling well, the study will be stopped for you.

With many research studies, there is a risk that someone who is not part of this research accidentally sees your personal information. Safeguards will be in place to minimize this risk by keeping your research records as confidential as possible. When the results of this research are published or presented at conferences, information that may identify you could be included. See the end of this document to select your preferences regarding your identifiable information.

Are there any benefits to me?

Although there may be no direct benefits to you, the results of this study may benefit others in the future. This research may benefit the understanding of the added value of using haptic feedback gloves for different setups. Providing valuable insights into refining VR technologies and uses for different applications.

Will I receive anything for participating?

You will receive a $15 gift card after completing your participation. The gift card will either be handed to you as a physical card on the spot or provided within two weeks of your completion. A bonus of $10 will also be awarded to the top 10% of performers once all participants have finished. Participants who do not complete the study in full will not be compensated, except in cases where participation is discontinued due to VR illness or skin irritation, in which case the full $15 gift card will be provided.

Who is the financial sponsor for this study?

The financial sponsor of this study is the United States Department of Defense.

Who could see my information?

Your research records may be shared and reviewed by the following groups:

- Representatives of the Oakland University Institutional Review Board and/or other regulatory compliance staff, whose job is to protect humans who are in research studies.
- Regulatory authorities who oversee research (Office for Human Research Protections, or other federal, state, or international regulatory agencies)
- The financial sponsor supporting the study and their agents or monitors.

De-identified data may be used or distributed to other investigators for future research use without additional informed consent from you.

What if I want to stop participating in this study?

If you want to stop participating in this study, you should tell the researcher, and then you will be free to stop your participation in this study.

Who do I contact if I have questions about this study?

Primary researcher Abed Aljundi, EC-464, phone number: (248) 402-3897, email: aljundi@oakland.edu
Secondary researcher Fares Al-Shubeilat, EC-464, phone number: (947) 201-6274, email: falshubeilat@oakland.edu
Secondary researcher Solaf Athamnah, EC-464, phone number: (248) 941-3215, email: solafathamnah@oakland.edu
Faculty Advisor Dr. Osamah Rawashdeh, EC-446, phone number: (248) 370-2866, email: rawashd2@oakland.edu
Faculty Advisor Dr. Wing-Yue Geoffrey Louie, EC-442, phone number: (248) 370-2860, email: louie@oakland.edu

Please select one of the following:

I consent for my photograph, video, and voice taken for this project to be used to train a machine learning model for a period of **3 years**.	
I consent for my photograph, video, and voice taken for this project to be used as part of a modified composite file or with my face blurred to train a machine learning model for a period of **3 years**. This means that **no single identity is recognizable.**	
I do not consent for my photograph, video, and voice taken for this project to be used to train a machine learning model.	

Please select one of the following:

I consent for my photograph, video, and voice taken for this project to be shown to developers for current and future research for a period of **3 years**.	
I consent for my photograph, video, and voice taken for this project to be shown to developers for current and future research as part of a composite file or with my face blurred for a period of **3 years**. This means that **no single identity is recognizable.**	
I do not consent for my photograph, video, and voice taken for this project to be shown to developers for current and future research.	

Please select one of the following:

I consent for my photographs, video, and voice taken for this project to be presented at scientific meetings or published in academic journals to illustrate research conducted by Abed Aljundi, Fares Al-Shubeilat, Solaf Athamnah, Dr. Osamah Rawashdeh, Dr. Wing-Yue Geoffrey Louie, and their collaborators from Oakland University for a period of **3 years**.	
I consent for my photographs, video, and voice taken for this project to be presented at scientific meetings or published in academic journals as part of a composite file or with my face blurred to illustrate research conducted by Abed Aljundi, Fares Al-Shubeilat, Solaf Athamnah, Dr. Osamah Rawashdeh, Dr. Wing-Yue Geoffrey Louie, and their collaborators from Oakland University for a period of **3 years**. This means that **no single identity is recognizable.**	
I do not consent for my photographs, video, and voice taken for this project to be presented at scientific meetings or published in academic journals to illustrate research conducted by Abed Aljundi, Fares Al-Shubeilat, Solaf Athamnah, Dr. Osamah Rawashdeh, Dr. Wing-Yue Geoffrey Louie, and their collaborators from Oakland University.	

For questions regarding your rights as a participant in human subject research, you may contact the Oakland University Institutional Review Board, 248-370-2762.

Signing the consent form

Your signature below means that you have read this form, or someone has read it to you and you agree to participate in this study.

You are not giving up any legal rights by signing this consent form. You will be given a copy of this form.

____

____

Print name of participant **Signature of participant**

Date _____________________________

Demographic Survey

Age: What is your age? _______ years (Leave blank if you prefer not to answer)

Gender: What is your Gender?

a) Male

b) Female

c) Other, please specify ________

d) Prefer not to answer

VR experience:

Have you ever used a VR headset? If so, how often?

i. Once

ii. A few times

iii. Regularly

iv. I have never used a VR headset

Have you ever used VR gloves? If so, how often?

i. Once

ii. A few times

iii. Regularly

iv. I have never used VR gloves

Preferred hand:

What is your preferred hand for most tasks?

a) Left

b) Right

Hand size: Please refer to the picture below for the following questions

What is the length of your palm? _______ inch

What is the width of your palm? _______ inch

Virtual Reality Sickness Questionnaire (VRSQ)

	Not at all	Slightly	Moderately	Very
General discomfort				
Fatigue				
Eyestrain				
Difficulty focusing				
Headache				
Fullness of head				
Blurred vision				
Dizzy (eyes closed)				

Presence Questionnaire

Question	Scale labels
In the computer generated world I had a sense of "being there"	not at all--very much
Somehow I felt that the virtual world surrounded me.	fully disagree--fully agree
I felt like I was just perceiving pictures.	fully disagree--fully agree
I did not feel present in the virtual space.	did not feel--felt present
I had a sense of acting in the virtual space, rather than operating something from outside.	fully disagree--fully agree
I felt present in the virtual space.	fully disagree--fully agree
How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?	extremely aware-moderately aware-not aware at all
I was not aware of my real environment.	fully disagree--fully agree
I still paid attention to the real environment.	fully disagree--fully agree
I was completely captivated by the virtual world.	fully disagree--fully agree
How real did the virtual world seem to you?	completely real--not real at all
How much did your experience in the virtual environment seem consistent with your real world experience ?	not consistent-moderately consistent-very consistent
How real did the virtual world seem to you?	about as real as an imagined world--indistinguishable from the real world
The virtual world seemed more realistic than the real world.	fully disagree--fully agree

Embodiment Questionnaire

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
It felt like the virtual body was my body					
It felt like the virtual body parts were my body parts.					
The virtual body felt like a human body					
It felt like the virtual body belonged to me					
The movements of the virtual body felt like they were my movements.					
I felt like I was controlling the movements of the virtual body.					
I felt like I was causing the movements of the virtual body					
The movements of the virtual body were in sync with my own movements.					
I felt like the form or appearance of my own body had changed					
I felt like the weight of my own body had changed					
I felt like the size (height) of my own body had changed.					
I felt like the width of my own body had changed					

System Usability Scale

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I think that I would like to use this system frequently					
I found the system unnecessarily complex					
I thought the system was easy to use					
I think that I would need the support of a technical person to be able to use this system					
I found the various functions in this system were well integrated					
I thought there was too much inconsistency in this system					
I would imagine that most people would learn to use this system very quickly					
I found the system very cumbersome to use					
I felt very confident using the system					
I needed to learn a lot of things before I could get going with this system					

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