

The Effects of Encountered-Type Haptics on Immersion, Presence, User Experience and Task Performance in Virtual Control Panel Environments

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Declaration

I declare that this dissertation is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other university.

Signed this 30th day of January 2023

A stylized, handwritten signature in black ink, consisting of several loops and a long, sweeping underline.

Kiren K. Padayachee

Abstract

Virtual Reality (VR) aims to immerse users in an experience that feels real. Passive haptic feedback enhances immersion, with users interacting with real-world analogues of virtual objects, as if directly encountered. Encountered-Type Haptic Displays (ETHDs) track users to dynamically provide this feedback, but cannot keep up with human movements, slowing them down, and negatively impacting the experience. Four experiments were conducted with the custom-built, high-speed, *Fast ETHD* system, to quantify its effects on aspects of the VR experience. The *VR Alien Shooter Game Experiment* entailed 25 participants shooting aliens, and answering modified versions of the Presence Questionnaire (PQ) and User Experience Questionnaire (UEQ), to answer “*What effects on immersion, presence and User Experience (UX) are observed in users as ETHD speed increases?*” Sentiment scores improved for the PQ aspects of *Possibility To Act*, *Quality Of Interface* and the UEQ aspect of *Efficiency*. Game performance improved in the *Total Aliens Hit*, *Aliens Hit by Normal and Double Shots*, *Aliens Hit by Laser and Big Shots*, *Alien Bullets Hit* and *Spaceship Damage* categories. The UEQ aspect of *Attractiveness* showed no effect on scores, with a decrease observed for *Dependability*. Participants had positive sentiments toward the system and experience, with average scores for *Perspicuity*, *Stimulation* and *Novelty* scales of the UEQ being 1.79, 2.27 and 1.33 respectively, the maximum of 3.00 being strongly positive sentiment. Users were not that sensitive to the speed profile range. Exposing users to more repetitions per speed, on a faster rig, would aid future studies. The *VR Fitts’s Test Experiment* had novice users performing the ISO/TS 9241-411 multidirectional tapping task for different haptic conditions, answering “*What task performance is achieved with a high-speed ETHD and how does it compare to zero-delay conditions and previous studies?*” The ETHD Haptics Condition resulted in a throughput of 2.23bps for 27 subjects, the Table Haptics Condition 3.53bps for 26 subjects, and the No Haptics Condition 3.70bps for 23 subjects. The ETHD’s lower throughput is attributed to the latency in the *Fast ETHD* system. A faster microcontroller, more optimised Computer Numeric Control (CNC) firmware, and incorporating predictive models for positioning is suggested to reduce latency, and training users to expert levels to improve throughput.

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To my family and friends, thank you for all your motivation and support throughout these many years. I can now finally fulfil my never-ending promises of a braai and smoked ribs “once I’m finished”. To my family, Mum, Dad, Pry, Aryan, Leerusha, Vidhya and Naren, thank you all for supporting me on this lengthy journey which has turned the word *master’s* into a swear word. I owe you all big time and I am going to make up for all the quality time sacrificed for studies. I love you all lots and I thank you all for everything you have done for me and for being my guinea pigs.

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Finally I would to thank all the people that brought Virtual Reality to where it is today. This project was the push I needed to dive into this field and it was the best decision I’ve ever made. Besides the new skills I’ve gained, this project allowed me, my family, friends, work colleagues and many strangers to finally try out this cool new thing called VR. I now see the power of this technology to inspire people

in completely new ways. My kids had the chance to be chased by dinosaurs, wield light sabers, be artistic and even fish to rock music. The adults got to feel like kids again, with the video proof to show how funny they looked while doing so. I got the chance to explore the International Space Station and to play *Half-Life: Alyx*, two things that are extremely rare for anyone to experience. I'm glad I got the chance to contribute even a tiny bit more to this awesome technology, and I cannot wait to see what it evolves into in the future.

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List of Symbols

The principal symbols used in this thesis are summarised below, and the first equation in which each symbol appears is given.

f	Cohen's f (Effect size for One-Way ANOVA), <i>Equation (5.1)</i>
p_i	n_i / N , <i>Equation (5.1)</i>
n_i	Number of observations in group i , <i>Equation (5.1)</i>
N	Total number of observations, <i>Equation (5.1)</i>
μ_i	Mean of group i , <i>Equation (5.1)</i>
μ	Grand mean, <i>Equation (5.1)</i>
σ^2	Error variance within groups, <i>Equation (5.1)</i>
f^2	Effect Size, <i>Equation (7.1)</i>
R^2	Goodness of fit, <i>Equation (7.1)</i>
R	Correlation Co-efficient, <i>Equation (7.1)</i>
m_1	Mean of group 1, <i>Equation (7.2)</i>
m_2	Mean of group 2, <i>Equation (7.2)</i>
σ_1	Standard deviation of group 1, <i>Equation (7.2)</i>
σ_2	Standard deviation of group 2, <i>Equation (7.2)</i>
$ m_2 - m_1 $	Delta of means, <i>Equation (7.3)</i>
d	Effect Size, <i>Equation (7.3)</i>

σ	Standard deviation, <i>Equation (7.3)</i>
p_i	n_i / N , <i>Equation (7.4)</i>
n_i	Number of observations in group i, <i>Equation (7.4)</i>
N	Total number of observations, <i>Equation (7.4)</i>
μ_i	Mean of group i, <i>Equation (7.4)</i>
μ	Grand mean, <i>Equation (7.4)</i>
σ^2	Error variance within groups, <i>Equation (7.4)</i>

List of Publications

- 1 K. K. Padayachee, S. P. Levitt, and K. J. Nixon, “Determining Human Hand Performance with the Oculus Quest in Virtual Reality Using Fitts’s Law,” in *SAICSIT Conference 2021. Proceedings of the South African Institute of Computer Scientists and Information Technologists September 2021*, pp. 1–24, Pretoria: Unisa Press and Unisa School of Computing, Oct 2021. <https://uir.unisa.ac.za/bitstream/handle/10500/28972/SAICSIT%202021%20PROCEEDINGS.pdf> 8

List of Videos

- 1 Encountered-Type Haptics for the Oculus Quest - Control Schemes: <https://www.youtube.com/watch?v=nQJ4EV1IXak> 6
- 2 Encountered-Type Haptics for the Oculus Quest - Detailed Explanation: https://www.youtube.com/watch?v=LxSI_9MnHPg 6

Nomenclature

Acronym definitions are provided at the first occurrence of each chapter.

2D	Two-dimensional
3D	Three-dimensional
ANOVA	Analysis of Variance
CAVE	Cave Automatic Virtual Environment
CNC	Computer Numeric Control
DAQ	Device Assessment Questionnaire
DOF	Degrees of Freedom
ETHD	Encountered-Type Haptic Display
HCI	Human-Computer Interaction
HMD	Head-Mounted Display
IPUXTP	Immersion, Presence, User Experience and Task Performance
JSON	JavaScript Object Notation
LED	Light-Emitting Diode
MRF	Magnetorheological Fluids
OLR	Ordinal Logistic Regression
PQ	Presence Questionnaire
RSD	Robotic Shape Display
RSE	Relative Standard Error
SUS	Slater-Usoh-Steed

UEQ	User Experience Questionnaire
UAV	Unmanned Air Vehicle
UDP	User Datagram Protocol
UX	User Experience
VE	Virtual Environment
VET	Virtual Experience Test
VR	Virtual Reality
VRFS	Virtual Reality Flight Simulator
WYSIWYF	What You can See Is What You can Feel

Chapter 1

Introduction

The importance of Virtual Reality (VR) systems and the benefits they bring to humanity are becoming increasingly evident in the modern world. VR technology is advancing swiftly, and while many are familiar with its entertainment value, it is also often used in training applications across a variety of disciplines. This includes training on medical procedures, construction, Computer Numeric Control (CNC) milling machines, mining, aircraft and for space missions [1–7]. The quality of the training from these applications and the resulting task performance is affected by the degree of immersion and presence provided by the virtual training environment [8,9]. Immersion is the extent to which a computer display can deliver the illusion of reality to the user's senses, with a highly immersed user not questioning if their Virtual Environment (VE) is real or fake [10,11]. Presence refers to a user's sense of belonging in the VE, with a highly present user being more engaged and concerned about the virtual world that they are in, rather than the physical world surrounding them.

The ideal VE provides a user with a high level of immersion and a strong sense of presence to create the perception that they are part of the virtual world [10]. This is achieved by stimulating the user's senses with high quality information from the VR devices used. While the audiovisual aspect of VR systems has become increasingly mature, the touch component has been researched using many strategies, but is yet to reach the level required for full mental immersion. Haptics refers to the ability to perceive the environment via the sense of touch, an Encountered-Type Haptic Display (ETHD) being one of the approaches that provides high quality haptic feedback in VR [12,13].

Users interacting with a VE assume that the laws of physics in the real world still apply, with their state of immersion immediately being broken when they reach out

to touch a virtual object, only to find that their hand moves directly through it [11]. Haptic feedback is provided by vibration, movement restriction, air vortices, and magnetic forces of repulsion and attraction, while acoustic positioning allow users to feel the presence of virtual objects while still allowing them to move through these objects [14–18]. Passive haptics is a specific type of haptic feedback that uses real-world replicas of virtual objects in the VE to provide the realistic, solid feeling of objects that the user expects [19]. These physical replicas allow the user to feel real properties of an object, such as position, orientation, shape, texture, weight, temperature and rigidity. ETHDs improve haptic feedback by using devices that have a wide range of motion to track the user movement and correctly position passive haptic objects to correspond to their virtual representations in a VE [13]. The devices move accordingly to encounter a user interaction with a virtual object in order to provide haptic feedback.

ETHDs come in many forms and have a variety of uses, including as industrial prototyping tools and for remote tele-operation activities such as surgical procedures [20]. Virtual experiences can be made more realistic, as ETHDs allow users to interact physically with the virtual objects that they see in the VE. When this added realism is applied to real world scenarios, ETHDs are useful aids in training simulations. More realistic simulations allow trainees to be better equipped for handling real-life situations, such as medical procedures and mining operations, compared to other methods such as manuals and training videos [21]. These types of realistic training simulations are reminiscent of the iconic scene from the science fiction motion picture *The Matrix* [22], in which the protagonist, Neo, is plugged into a VR simulation via a neural interface to learn martial arts. After a few seconds, Neo exclaims “I know Kung Fu.” While current technology is certainly far from this vision of the future, the use of VR and ETHDs in training applications provide improvements in the level of knowledge passed on to trainees. These visions of future technology depicted in works of science fiction stoke the imagination, which drives us to push technology forward to provide more realistic experiences.

1.1 Research Problem

Latency in a system refers to the delay between an input and the desired response [23]. In the case of ETHDs, latency is the delay that results from processing, and the motion that occurs between a new instruction to change the position and when it has finally come to a stop at the new position. Pure, passive, haptic feedback objects

provide zero-latency interactions, as they are not in motion. When a user touches one of these passive haptic feedback objects, the interaction is immediate and realistic. However, ETHDs cannot provide zero-latency interactions as they are mechanical devices, and need to reposition objects rapidly in 3D space with as little latency as possible, to provide the sensation of interacting with a solid, immovable, virtual object [24]. A wide space to position these objects corresponds to a large virtual space to explore, with ETHDs providing the touch feedback needed for immersive VR, making them an attractive solution.

However, consistency between ETHD capabilities varies widely, with only industrial quality robot arms being capable of fast movement speed, having the strong counterforces required to simulate solid virtual objects and the wide enough reach needed for an effective display, their cost making them unaffordable for consumer applications. Smaller robot arms will have far slower speeds, shorter reach and smaller counterforces, such that a user pushing on it would move the device itself. Yokokohji *et al.* developed a VR system with an ETHD that worked as intended, but noted that the Puma 560 robot used as the display was not able to keep up with users' quick and erratic movements [25]. Gruenbaum *et al.* implemented an ETHD system using the four Degrees of Freedom (DOF) Adept 1 Manipulator robot arm and stated that their system was not adequate for VR training systems, as the users were easily able to move faster than it could track [24]. Araujo *et al.* developed their Snake Charmer ETHD system, which used the small Robai Cyton Gamma 300 robot arm [26]. As a commodity robot arm, this had limited velocity and spatial resolution, and was unable to provide the necessary counterforce when users pushed on it to simulate solid immovable objects. Other devices used as ETHDs, such as aerial drones, also share the same tradeoffs [27]. Creating a good ETHD system is therefore a balance between tracking speed, counterforce capability, reach and cost.

One of the most common issues with ETHD systems is the slow tracking of user movements, with users needing to wait for the device to reach their position or being forced to match the slower speed of the device. This forced unnatural movement results in reduced immersion and presence and an overall poor experience [24]. If the user is required to perform tasks within the VE, such as in training applications, the reduction in quality of these factors results in reduced task performance.

There are many studies on VEs, VR and haptics related to measuring Immersion, Presence, User Experience and Task Performance (IPUXTP) to evaluate the effectiveness of virtual experiences [8, 9, 28–37]. UX refers to a person's perceptions and responses from using a product, system or service [38], while user peripherals

are measured on task performance to determine usefulness of these devices to the user [39,40]. This task performance is expressed as throughput, which is a metric that combines a user's speed and accuracy with a device. ETHDs, which are designed to complement VR experiences, are lacking in studies utilising these measurements, and have focused on measuring the physical capabilities of these devices, such as force feedback, speed, latency and tracking accuracy [24–27,41]. Studies are lacking on the utilisation of these methods to investigate the effects of ETHDs on IPUXTP in VEs.

1.2 Research Aim

ETHDs can be improved to provide better experiences by understanding the relationship of ETHD speed to IPUXTP, with empirical data aiding in the design of new displays, and comparing and improving on existing designs. Measuring the user's experience is therefore vital to determine how effective an ETHD is. The relationships between the physical capabilities of ETHDs and the user's perception and interactions in the virtual world need to be examined, to address the gap in literature regarding these relationships. The basis of this study theorises that ETHD speed directly influences the IPUXTP of users in VE's, with empirical data of the required speed to match hand movement for nominal IPUXTP being required to build optimal displays.

The aim of this study is:

- as a primary goal, to investigate the effects of ETHD speed on IPUXTP in VEs and,
- as a secondary goal, to design and build a low-cost, grounded, fixed platform ETHD with a focus on speed and user safety.

Statistical analysis was used to determine if users were able to perceive the differences in IPUXTP in VEs for varying speed profiles of the ETHD, the results potentially contributing to the advancement of ETHD technology to improve the VR experience.

1.3 Research Scope

An ideal ETHD is able to provide users with perfect interactions that are indistinguishable from those experienced in real life. There would be zero latency for haptic feedback, the user would be able to completely explore an object's shape and could also potentially be able to manipulate an object's position and orientation. They would also be able to explore a virtual space with unlimited size in 3D with both hands or even their entire body.

Some limitations were implemented to simplify the study, these being that the interactions are limited to the index finger of the user's dominant hand, interactions being limited to 2D space, objects in the scene being fixed in position and orientation, and the user being able to explore the objects' shapes but not able to move them around. The intention with the ETHD developed was a proof-of-concept that attempted to minimise latency and maximise user safety within the budget constraints of the project.

This study required human volunteers, the number of participants required being determined using power analyses and reviewed for feasibility with regards to time. Two tests were conducted, the VR Alien Shooter Game Experiment having 25 participants, while the VR Fitts's Test Experiment had 27 participants for the ETHD Haptics Condition sub-experiment, 26 for the Table Haptics Condition and 23 for the No Haptics Condition.

1.4 Research Question

The research question is:

What is the effect of Encountered-Type Haptic Display speed on Immersion, Presence, User Experience and Task Performance in VEs?

The main research question can be broken down as follows:

RQ1

What effects on immersion, presence and UX are observed in users as ETHD speed increases?

RQ2

What task performance is achieved with a high-speed ETHD and how does it compare to zero-delay conditions and previous studies?

Two experiments were conducted to answer these questions, the first being the VR Alien Shooter Game Experiment that was conducted to answer RQ1, with the VR Fitts's Test Experiment being conducted to answer RQ2. The *Fast ETHD* system that was custom built for these experiments, consisted of a high-speed hardware ETHD and VR software implementations of the ISO/TS 9241-411 multidirectional tapping task and a game reminiscent of the classic arcade shooter *Space Invaders* [42]. The jerk and acceleration configurations for the ETHD were kept constant to ensure that the focus for the research questions were on its speed profile configurations, which were set as percentages of its maximum speed.

Videos

Videos on these experiments can be viewed at the following URLs:

Encountered-Type Haptics for the Oculus Quest - Control Schemes

<https://www.youtube.com/watch?v=nQJ4EV1IXak>

Encountered-Type Haptics for the Oculus Quest - Detailed Explanation

https://www.youtube.com/watch?v=LxSI_9MnHPg

1.5 Dissertation Structure

This dissertation is structured in the following manner:

- **Chapter 2. Literature Review: Virtual Reality and Encountered-Type Haptic Displays:** A literature review is presented on VR technology, its use in training simulations and on haptic feedback for VR. It also focuses on passive haptics and a special case of passive haptics called encountered-type haptics which make use of ETHDs. Research is presented on what kind of speed capabilities are required of ETHDs to keep up with human hand movements.

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- **Chapter 3. The Fast ETHD System:** The design of the *Fast ETHD* system that will aid the two experiments is presented, with the requirements and design decisions being detailed as well as the obstacles encountered during the development phase. The system features and operation are given followed by quantitative performance observations.
 - **Chapter 4. Literature Review: Immersion, Presence and User Experience:** A literature review is presented on the concepts of immersion, presence and UX experienced by users in VEs, with existing tools for evaluating these concepts quantitatively being discussed. The Presence Questionnaire and User Experience Questionnaire were the final tools chosen to measure these concepts, their selection being based on their construct validity and internal consistency.
 - **Chapter 5. VR Alien Shooter Game Experiment:** A game experiment developed for this study, similar to the classic arcade shooter game *Space Invaders*, is presented to answer RQ1. Participants were required to play this game while getting haptic feedback from the *Fast ETHD* system. The ETHD speed was varied as the treatments and participants were required to answer modified versions of the PQ and UEQ for each speed profile. The results were used to determine the effect that ETHD speed has on immersion, presence and UX. The effect on game performance was also analysed, with experimental design, setup, methodology and procedures being presented, followed by the results, analysis and discussion on the observations.
 - **Chapter 6. Literature Review: Task Performance:** A literature review on human performance using Human-Computer Interaction (HCI) devices is discussed. The focus is on Fitts's Law, which states that the time taken to move a pointer to a target is determined by the distance to the target and the size of the target. The ISO 9241-9 and ISO/TS 9241-411 multidirectional tapping task used to verify Fitts's Law are discussed. Previous studies using these tests to determine throughput of devices are discussed with a focus on Fitts's Law studies in VEs.
 - **Chapter 7. VR Fitts's Test Experiment Methodology:** A second experiment was designed to answer RQ2, the VR Fitts's Law Experiment making use of the ISO/TS 9241-411 multidirectional tapping task in a VE using the *Fast ETHD* system to provide haptic feedback. Throughput using Fitts's Law will be determined for different haptic conditions. The experiment methodology, equipment, software, user interfaces, data capturing, data transformations, sample size estimations, participant selection, experiment procedures and data analysis applicable to each of these haptic conditions are provided.

- **Chapter 8. VR Fitts’s Test Experiment Results:** Three haptic conditions were used as treatments for the VR Fitts’s Law Experiment: the No Haptics, Table Haptics and ETHD Haptics Conditions. The experiment methodologies discussed in Chapter 7 are applied to each of these conditions, with the final results and discussions being presented for each haptic condition, as well as their respective final grand throughputs. The comparisons between the three conditions as well as to other devices and VE setups from previous Fitts’s Law studies are discussed.
- **Chapter 9. Discussion:** Threats to validity are discussed for both experiments, as are their construct, internal and external validity, as well as a high-level interpretation of the experiment results.
- **Chapter 10. Conclusion:** This chapter reviews the contributions made from this study, provides recommendations for future research, and makes final concluding remarks on the state of VR, as well as the reason it is necessary and beneficial to continue developing this technology along with haptic feedback technology.

1.6 Contributions Made

The following contributions have resulted from this study:

- The design of the 2D tabletop *Fast ETHD* system that provides encountered-type haptic feedback in a VE, which is focused on speed and user safety.
- At the time of writing, this appears to be the first study that investigates how the speed of an ETHD affects user immersion, presence and UX.
- At the time of writing, it appears that this is the first study done that aims to evaluate user task performance using an ETHD. Fitts’s Law and the ISO/TS 9241-411 multidirectional tapping task are used to determine the throughput of the *Fast ETHD*, which is compared to the zero-latency haptics conditions and other VE setups with haptic feedback from previous studies.
- A paper titled *Determining Human Hand Performance with the Oculus Quest in Virtual Reality using Fitts’s Law* was submitted and accepted for the SAICSIT 2021 conference [43]. This paper presented the results from a preliminary study on the hand tracking feature of the Oculus Quest, the feature’s throughput being evaluated using the ISO/TS 9241-411 multidirectional tapping task.

A more detailed account of these contributions can be found in Section 10.2.

1.7 Theoretical Framework

VR is effective for providing the user with a good experience when it delivers high quality information to their senses, with an important component being touch. There are many methods to integrate the haptic component of touch into the VR experience. A good VR experience presents users with a high level of immersion, a strong sense of presence and an overall excellent UX which will, in turn, result in better task performance within the VE. These concepts will be explored briefly here with more detailed literature reviews presented in Chapters 2, 4 and 6. The theoretical framework presented takes guidance from Osanloo and Grant [44].

1.7.1 Haptics

Many solutions have been established to enable haptics in the VR experience, each with its own advantages and disadvantages. There is currently no perfect haptic technology capable of completely fooling a user immersed in a VE into believing that they are able to physically interact with virtual objects while still having the natural sensations they are accustomed to in real world interactions.

The most common haptic technology available is severely limited in providing realistic interactions with VR objects. The most common haptic technology for VR, VR gloves, even with vibrational capabilities or movement restriction techniques, merely alerts users of colliding with a virtual object, but when they attempt to push through it in the VE, they move directly through it, breaking the immersion. Passive haptics remedies this problem by providing users with real world replicas of virtual objects to interact with, which allow the user to feel real world properties of an object such as position, orientation, shape, texture, weight, temperature and rigidity [19]. However, passive haptics is limited because it can only provide a fixed number of objects in the VE.

McNeely noted the problem of VR users passing through VR objects and the need to provide realistic feedback through “solid” virtual objects. McNeely proposes that an external robot arm unattached to the user’s body could provide users with the necessary forces when interacting with virtual objects on a just-in-time basis, which resulted in the proposal of *Robotic Graphics* [13]. Robotic Shape Displays (RSDs)

would employ these robot arms to track the user's arm position and move to the corresponding real word position of a virtual object that the system anticipates the user to reach out to. The robot arm will then wait at this position until the user encounters it, hence the term Encountered-Type Haptics or Robotic Graphics, which brings a much needed dynamic component to VR to provide a more realistic experience [45].

A common flaw in previous ETHD designs using robot arms is that they were not able to track the user's erratic motions quickly enough [24–26, 46]. This problem of the device not following the user fast enough forces the user to move slower and unnaturally for the device to catch up [24]. However, this is not ideal, as maximum immersion in a VE requires the user to be able to move naturally without having to focus on their movements.

A detailed literature review on VR, haptics and ETHDs is presented in Chapter 2.

1.7.2 Immersion and Presence

Immersion in a VE is defined as the extent to which a computer display can deliver an *inclusive, extensive, surrounding* and *vivid* illusion of reality to the user's senses. Presence refers to the state of consciousness of the user as a feeling of being a part of the VE [10]. Mihelj and Podobnik state that mental immersion requires the user to be preoccupied with their existence within the VE to such an extent that they stop questioning whether it is real or fake [11].

Two measurement tools frequently cited in VR literature are that of the Slater-Usuh-Steed (SUS) Questionnaire by Slater *et al.* [35] and the Presence Questionnaire (PQ) by Witmer and Singer [32]. The SUS Questionnaire focuses on the psychological aspect of presence and has questions that evaluate the experience of users in VEs on their subjective experience of presence. The SUS Questionnaire queries the user about their sense of being a part of the virtual world, to the extent that the virtual world became their 'new reality'. The PQ measures the degree to which users experience presence in a VE, with both having been used in many VR studies to measure the component aspects of immersion and presence [8, 9, 33].

A detailed literature review on immersion and presence as well as the SUS Questionnaire and PQ measurement tools is presented in Chapter 4.

1.7.3 User Experience

The definition of UX according to the ISO 9241-210 specification is “*a person’s perceptions and responses resulting from the use and/or anticipated use of a product, system or service*” [38]. Providing a good UX is important to ensure positive responses from users, being able to measure UX quantitatively in an efficient and reliable manner is therefore important to evaluate a product, system or service, the data being used to make improvements if required.

Questionnaires have been developed to quantitatively evaluate UX according to these criteria, with Laugwitz *et al.* having developed the User Experience Questionnaire (UEQ), the questions being grouped into categories of *attractiveness*, *perspicuity*, *dependability*, *efficiency*, *novelty* and *stimulation* [37]. Chertoff *et al.* developed the Virtual Experience Test (VET), which measures the holistic experiences of users in VEs based on five elements of experience: *sensory*, *cognitive*, *affective*, *active(personal)* and *relational(social)* [47].

A detailed literature review on UX as well as the UEQ and VET measurement tools is presented in Chapter 4.

1.7.4 Task Performance

Measuring task performance quantitatively is one way to effectively evaluate the usefulness of a device. The ISO 9241-9 specification and its follow-up, ISO/TS 9241-411, focus on evaluating interactive computer pointing devices, such as mice and joysticks, by measuring task performance when using these devices [40, 48]. The ISO/TS 9241-411 2D multidirectional tapping task is a test that makes use of Fitts’ Law to quantitatively evaluate task performance on the metric of *throughput*. Fitts’ Law is a model that is used to predict human movement towards a target and has been widely used to study relationships for HCI. Specifically, it states that the time taken to move towards a targeted area is related to the size of the target and the distance to it. The ISO/TS 9241-411 2D multidirectional has been widely used to evaluate pointing devices and tasks.

A detailed literature review on task performance as well as the ISO/TS 9241-411 multidirectional tapping task is presented in Chapter 6.

1.8 Conceptual Framework

The conceptual framework presented takes guidance from Maxwell, with the process of a user interacting with a VE complemented by an ETHD being depicted in Figure 1.1 [49]. The user reaches out to touch a virtual object in the VE and the ETHD positions a real world analogue in the corresponding position for the user to physically feel, as depicted in Figure 1.2. The ETHD needs to move fast enough to position the real world object for the user to encounter to prevent a noticeable delay. Therefore, the speed of the ETHD has an effect on the quality of the haptic feedback delivered. The audiovisual feedback from the VR headset worn by the user combined with the haptic feedback component delivered by the ETHD directly affect the immersion, presence and UX experienced by the user in the VE. If the user is performing a task within the VE, as is normally done in games and training applications, the task performance is affected by the previous components in the process flow.

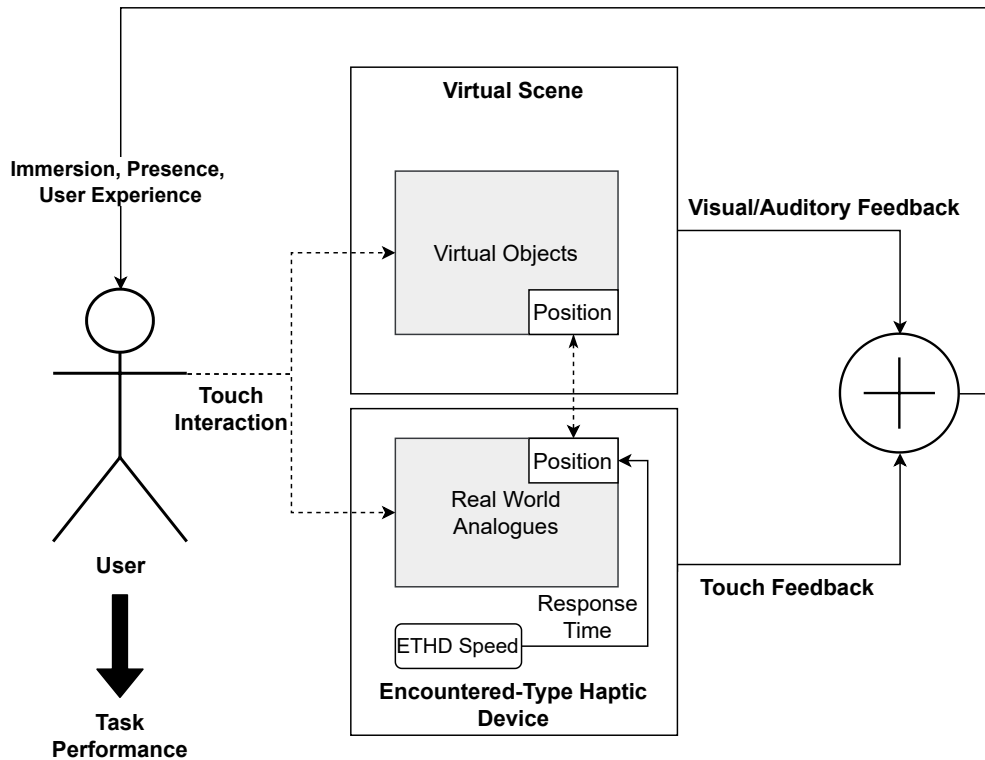


Figure 1.1: Inputs, outputs and process of an interaction with a VR scene complemented by an ETHD.

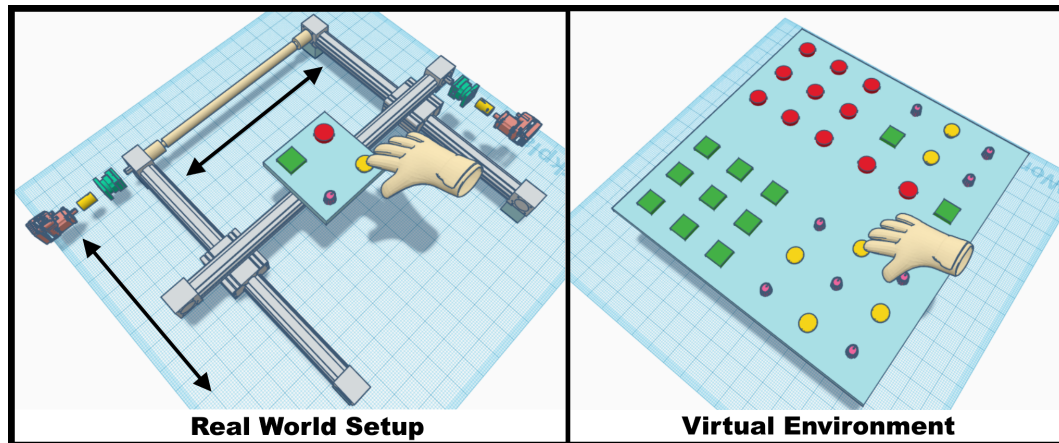


Figure 1.2: A typical scenario where the user reaches out to touch a virtual object in the VE and the ETHD positions the correct real object for haptic feedback.

1.8.1 Factor Overview

Starting with the user, the touch interaction is the first input factor in the process, being multifaceted in that it is affected by many variables. Large variations between users can occur in terms of perception of visual and touch feedback as well as hand-eye coordination abilities, with age, health, mental and physical abilities affecting hand movement speed. Previous experience with computers, VR and video games would have an effect on how comfortable users are in interacting with VEs and performing tasks within them. Owing to the large variability affecting touch interaction, these will be considered as confounding variables, with an attempt to reduce them, as well as learning and order effects, being made in this study.

To reduce these effects, participants were trained to use the equipment and allowed to use it freely for a short while to become comfortable with it, with randomisation of the treatment order being implemented to further reduce the effects of confounding variables. Breaks were intermittently held during the experiment to prevent fatigue, which would affect the results [50].

The audiovisual quality of the virtual scene has a direct impact on the experience of the user, with more realistic graphics and sounds improving the experience in the virtual world. A high quality display to impart this information was necessary to provide the best experience, the study aiming to produce a simple high quality virtual scene with a high quality VR headset for display, their quality remaining constant and not regarded as a factor.

The quality of the touch feedback delivered by the ETHD is determined by its speed

in responding to changes in user movement, force feedback capability, physical size and reach, which correspond to the virtual volume that the user can explore. For this study, the force feedback, size and reach of the ETHD will be fixed, with the ETHD speed being the main variable determining the quality of the display, as it is directly involved in responding to changes in user movement and repositioning objects for them to encounter. Therefore, the ETHD speed will be regarded as an independent factor, and designed to be as accurate as possible, due to its mechanical nature. It can be assumed that there will be small fluctuations in the intended speed as well as the accuracy of positioning real objects corresponding to the virtual counterparts, the errors in speed and accuracy being regarded as confounding factors.

User hand movement speed must be considered as the ETHD must be able to keep up with their movements. Based on previous research, the minimum speed for the ETHD to operate to provide an adequate experience in the VE is 0.5m/s, with no limits being imposed on the maximum speed [51–56]. However, for practicality and cost reasons, 1m/s should be acceptable based on maximum human movement speed, with acceleration to reach intended speeds being as high as possible within practical limitations.

The immersion, presence and overall UX experienced by the user depends on the audiovisual quality from the virtual scene and the quality of the touch feedback from the ETHD. These are important factors to consider to evaluate the system as a whole, with immersion, presence and UX being regarded as dependent factors. The PQ and UEQ were chosen as the most appropriate tests for this study since these were specifically designed to evaluate these concepts.

Users were asked to perform a task and their performance evaluated, this being necessary to evaluate the usefulness and usability of the ETHD. This is also an important metric that can be used as a measure to aim for in designing ETHDs. Task performance depends on the factors of immersion, presence, UX, ETHD speed, and audiovisual and touch feedback quality, and was regarded as a dependent factor.

An appropriate test is required that can evaluate task performance correctly, with the ISO/TS 9241-411 multidirectional tapping task being used. This requires users to interact with targets, arranged in a circle, that vary in size and distance from each other, with target size and distance being regarded as independent factors. The ETHD ran at its maximum stable speed, with results being compared to zero-latency conditions, as done in previous studies. Teather *et al.*, and Joyce and Robinson, used conditions for mid-air interactions with no haptics and a flat surface, the haptics

condition being considered an independent factor [29, 31].

1.8.2 Factors of Interest for this Study

The following factors are chosen to be investigated in this study:

- Independent factors
 - ETHD Speed: the main independent factor of interest as it will directly affect the user experience.
 - Target Size: essential for the ISO/TS 9241-411 multidirectional tapping task.
 - Target Distance: essential for the ISO/TS 9241-411 multidirectional tapping task.
 - Haptics Condition: essential to compare the ETHD results to zero-latency conditions.
- Dependent factors
 - Immersion: a rating of the quality of the information displayed to the user to create the illusion of the virtual world [10].
 - Presence: a rating of the ability of the system as a whole to make the user feel like they are a part of the virtual world [10].
 - User Experience: a rating of the user's overall perception and response to the VE they are interacting with [38].
 - Task Performance: measured as throughput in bits per second, is crucial in determining the usefulness and usability of the ETHD and will also be used to quantitatively compare it to other pointing devices [40, 48].

The other factors of perception of visual and touch feedback, hand-eye coordination abilities, age, health, mental and physical abilities, previous experience with VR and video games, as well as errors in ETHD speed and positional accuracy were regarded as confounding factors. The experiments for this study implement a Randomised Complete Block Design to reduce the effects of these factors and any others that were unknown.

Two experiments were conducted:

- *VR Alien Shooter Game Experiment* to determine the relationship of ETHD speed to immersion, presence and UX, with variable ETHD speeds.
- *VR Fitts's Test Experiment* keeps the ETHD speed at maximum and varies the haptic condition to determine the task performance of each condition and how they compare to each other.

1.9 Significance of the study

The findings of this study will assist in ensuring a more realistic VR experience. With VR becoming increasingly accessible to consumers and used more extensively in training applications, among others, effective haptic technology will be the next step to ensuring a realistic experience. The ETHD design proposed for this study is intended to be able to provide effective tracking speeds to allow the user to move naturally without having to adapt to the limitations of the device. ETHDs have the potential to provide a more dynamic experience by allowing users to interact with solid feeling virtual objects. VEs could change often as the ETHD would be able to accommodate these changes and multiple VEs with different layouts. To achieve the solid feeling of virtual objects, the device should quickly track user movements, provide effective counterforce to simulate solid objects, and provide enough reach so that the user has a wide virtual space to explore. VR training applications would greatly benefit from a reliable ETHD that can keep up with users for a seamless experience, which would improve the quality of the training.

Questionnaires for rating a user's immersion, presence and UX and tests for measuring task performance on a device are readily available and have been used in other VR studies. Therefore, these tools should also provide great insight into the use of ETHDs [32,37]. This study should show that evaluating ETHDs on these concepts empirically will be beneficial in the design of future ETHDs and improvements on existing designs. Having empirical data on how users interact with ETHDs and how these devices affect their overall experience gives far more insight into the use of these devices than just their physical capabilities.

This design, while not being able to provide as many DOFs as robot arms, is focused on speed and positional precision, the intention being to provide an effective ETHD experience while potentially being far more cost effective than expensive robot arms. Another factor limiting the widespread use of ETHDs is the cost of the devices. The design of the ETHD proposed for this study will incorporate linear actuators and

stepper motors instead of the common use of robot arms.

The results are intended to improve the performance of ETHDs, which will enable VEs with high quality haptics to provide higher levels of immersion and presence. ETHDs with fast tracking speeds can provide high quality haptics, while a low-cost, high-speed ETHD would enhance VEs, especially in training applications. Therefore, a low-cost, high-speed ETHD would increase the immersion, presence and UX experienced in VR training applications and improve the task performance of trainees.

Chapter 2

Literature Review: Virtual Reality and Encountered-Type Haptic Displays

This chapter provides a literature review on the concepts of Virtual Reality (VR) and how effective it is in aiding training simulations. Haptic feedback is then discussed and how it improves the VR experience, and divided into its specialised forms of passive haptics and encountered-type haptics which makes use of Encountered-Type Haptic Displays (ETHDs). These devices should be able to keep up with human hand movements to provide haptic feedback. Studies on human hand movements are evaluated to determine what speeds are acceptable for ETHDs to accomplish this goal. VR setups that use ETHDs require tracking of human hand movements, with different setups being discussed to determine which will be the most appropriate for this study.

2.1 Introduction

Virtual Reality (VR) is a technology that, until recently, was limited to well-funded research groups, the general public mainly regarding it as belonging in the realm of science-fiction. Today it is readily available to be used for entertainment in homes and through cellphones, it's versatility enabling it's use in training, design and tele-operation. It is increasingly being used in training applications, which now occurs across a variety of disciplines from factory machinery to astronauts for the International Space Station [57,58].

This study recognises the importance of haptic feedback to improve the immersion

and overall experience of the user interacting with a Virtual Environment (VE). Touch feedback brings a new element to the virtual experience and is vital for pushing the technology forward towards the ultimate goal of the user not being able to distinguish the experience from reality. However, there are many different methods of providing this touch feedback with varying degrees of effectiveness. In choosing the type of haptic technology to build and study, it is important to compare the different methods of touch feedback available, their advantages and disadvantages, and importantly, how effectively the technology is able to convey this to the user.

The following review of literature will look at what qualities are ideal for this touch feedback to have to be effective for the user's experience. It will then review a few different implementations of haptic feedback, and their effectiveness in conveying touch feedback. The passive haptics implementation in particular will be evaluated and evidence presented as to why this was chosen as the best type to explore. Focus will be given to Encountered-Type Haptic Displays (ETHDs) due to this implementation's ability to bring a much-needed dynamic element to the otherwise static behaviour of passive haptics.

One of the goals of this study is to produce a low-cost high-speed ETHD that is capable of keeping up with normal user hand motions and investigate its effects on the VR experience. An understanding of the speeds a human hand is capable of achieving must first be established to effectively determine how fast the ETHD needs to be.

This study also aims to make the virtual experience as natural as possible to participants, one way being to allow the user to interact with the VE with their hands rather than with controllers. Many methods are available to allow this type of interaction with varying degrees of success, these being evaluated to determine which would be the most appropriate for this study.

2.2 Virtual Reality and Training

Advanced systems with VR Head-Mounted Displays (HMDs) that were once only found in research initiatives such as the NASA Ames VIEWlab Project can now be found in people's homes [59]. The Sony PlayStation VR, Oculus Rift and Quest and HTC VIVE are examples of currently available commercial VR products that allow users to be immersed in VEs [60–63]. These are often used for entertainment purposes in the form of video games, the many applications including tele-presence,

prototyping, music and the tele-rehabilitation of patients [64–67].

VR is also used in training applications, it's extensive use being due to it sometimes being more effective than traditional training methods. Chao *et al.* noted that ideal training performance can be observed from trainees under conditions for proper mental workload [21]. They observed that that VR is a more effective training tool than traditional methods such as technical manuals and multimedia films, while performance measurements from trainees showed that it was the best training method, especially for complex tasks. Chao *et al.* correlate this to the lower mental workload observed with VR compared to technical manuals and multimedia films.

Lin *et al.* investigated training operators of Computer Numeric Control (CNC) milling machines with VR, and found a significant reduction in training time in VR versus reading the manual for the machine [1]. The number of errors on real CNC machines after the training was much lower in the VR training group than the group that read the manual, and the transfer of skills in the former was significant, particularly regarding procedural skill tasks.

Sacks *et al.* compared safety training of construction workers with traditional methods versus VR and found that there was a significant advantage when being trained on the latter [2]. They noted that workers in the VR training group were able to maintain full focus during the training compared to the traditional method group which tended to lose concentration and needed breaks.

Van Wyk and de Villiers assessed the use of VR training for safety in the mining environment and stated that it is far cheaper than building real full-scale training environments [3]. It can be used to expose users to situations that would normally be too dangerous to interact with in real life, this type of training also allowing for a wide variety of scenarios to expose trainees to.

A laparoscopy is a surgical procedure that is done to inspect the organs within the abdomen by inserting a tiny camera. A study by Grantcharov *et al.* showed that trainees who had VR training performed laparoscopic cholecystectomy faster, with few errors and fewer unnecessary movements than those in the control group who had no extra training [4]. Larsen *et al.* had similar results with trainees being trained in VR and then performing laparoscopic salpingectomy [5]. They also noted that, based on a rating scale, the VR trainees displayed scores equivalent to the experience gained after 20-50 laparoscopic procedures compared to the control group, whose scores were equivalent to the experience gained from less than five procedures.

Training for human spaceflight with VR goes back decades, with Loftin and Kenney training the ground-support flight team on the extravehicular activities planned using VEs for the Hubble Space Telescope repairs after its initial launch [7]. The survey results from the trainees showed that by being initially exposed to the objects, environments and procedures that they would be working with, the training had a positive effect on their job performance during the actual mission.

During the first few days of spaceflight, many astronauts experience the medical conditions known as Space Motion Sickness and Spatial Disorientation, which are caused by conflicts between the senses in a microgravity environment, unlike under normal gravity conditions where these senses are in agreement, and usually results in reduced activity. Stroud *et al.* found that those who had variable orientation training in a VR simulator not only displayed faster task completion times than those with fixed orientation in a follow up session, but that they also reported far less motion sickness than the fixed orientation group [68]. The results suggested that this type of training in a VR simulation can be an effective tool for spaceflight.

Aslandere *et al.* created a Virtual Reality Flight Simulator (VRFS) by integrating the commercial flight simulator software X-Plane, with the VRFS showing promise of being used for pilot training in the future [6]. Task performance in this system was reduced due to the users not knowing when they were touching the virtual buttons, thereby increasing the miss rate. Aslandere *et al.* concluded that the solution to this problem would be to use a physical mockup of the virtual cockpit, but that this would be expensive and make the VRFS dependent on a particular aircraft type. In a follow-up study where the volume of target buttons was varied to accommodate this problem, the authors reported that a physical mockup of the virtual cockpit would be a solution to this problem [69]. The positive effects that VR can have on training is evident from these studies, with advances having many more potential benefits for training and many other applications in VR.

2.3 Haptics

As mentioned by the studies conducted by Aslandere *et al.*, task performance in their systems could have been improved by including a physical mockup of the virtual cockpit, implying that the touch component in a VE is also important. The sense of touch is important as it provides the information that is needed to interact with the environment and others, and is therefore essential for human survival [70]. Being able to interact with objects in a VE combined with the ability to actually feel their

presence brings in a level of immersion that feels far more natural to the user [71]. Hayward *et al.* state that the word haptics refers to the ability to perceive the environment via the sense of touch [12]. Haptic devices allow the user to feel virtual objects, as though they were directly encountered, with various methods having been used to provide tactile feedback, depending on the interaction involved [70].

The sensation of grasping objects in VR is usually achieved by exerting forces on the fingers to restrict movement via a VR glove. The Rutgers Master II-ND glove provides force feedback to the fingers via pneumatic actuators that are attached to the palm and fingers [72]. CyberGlove System's Cybergrasp and Dexta Robotic's Dexmo [14, 73] gloves use electrical actuators located over the hand. Magnetorheological Fluids (MRF) are fluids composed of a base liquid and magnetic powder, and are able to change viscosity when a magnetic field is applied [74]. The Magnetorheological Actuated Glove Electronic System (MRAGES) was created to show that MRFs could be used to provide haptic feedback [75]. This glove applies the magnetic field to the MRF by activating an electromagnet, which increases the viscosity of the fluid to create the stiffness required to restrict the movement of the fingers.

Haptic methods that do not restrict movement include the use of touchless sensing techniques to feel the presence of a virtual object. Neurodigital's GloveOne and the Manus VR have vibrotactile actuators that are embedded in the fabric of the glove to provide vibrations on the back of the hand when there is contact with a virtual object [16]. Disney's AIREAL negates the need for VR gloves by firing directed air vortices at the user, which gives the user temporary gentle force feedback as the vortices are short lived [18]. Some haptic systems such as Ultrahaptics, Haptomime, Haptoclone and Mistable eliminate the need to use a VR glove by using 2D phased arrays of ultrasound transducers to create force using acoustic radiation [76]. This creates many points in the air that are individually perceivable, thus providing tactile feedback, this method having been expanded to create discernable 3D shapes in mid-air.

The FingerFlux project is focused on touchscreen haptics and expands on the ultrasound haptic feedback methods by using a 2D array of electromagnets. The user's finger has a narrow, cylindrical, permanent magnet attached to it that enables interaction with the grid of electromagnets [17]. When they interact, the user is able to feel attraction, repulsion, vibration and directional haptic feedback. When an electromagnet's polarity is set to repulse the fingertip's permanent magnet, the user can immediately feel the counterforce at that position. Butterfly Haptic's Maglev 200 System is essentially a magnetically levitated mouse that allows six Degrees of

Freedom (DOF) movement to manipulate objects in a VE, the base of the mouse that provides the electromagnetic repulsion being desk mounted to limit the range of movement [77].

The above methods of haptics presented are examples of *active haptics*, as the actuators in these devices controlling the feedback is done by computer, based on the interactions between the user and the VE [30]. However, there are clear limitations to the effectiveness of these methods in providing haptic feedback, as they still allow users to pass directly through virtual objects. This is not an accurate representation of real life where objects are mainly solid and cannot be passed through in a ghost-like fashion. Worn-type devices such as VR gloves feel unnatural to wear and those that project forces on the user do so too weakly to feel realistic.

2.4 Passive Haptics

When users interact with a VE, they automatically assume that it will obey the laws of physics as experienced in the real world. However, one of the most common unnatural property of VEs is not being able to actually feel virtual objects via sensory touch, enabling users to pass directly through them [33]. Users merely have to reach out to grab a virtual object and feel nothing but air to quickly re-asertain that they are in a simulation [26]. This unnatural property is the same reason why users could not reliably tell when their hands were touching the virtual buttons in the study done by Aslandere *et al.*, who concluded that a physical mockup of the virtual cockpit would have solved this problem, this being an example of *passive haptics* [6].

Passive haptics is a special type of haptic feedback that remedies this issue by using real world objects that are either exact replicas of the virtual objects or low fidelity versions for the user to interact with. Passive-haptic devices provide feedback to the user due to their shape and texture, as well as other physical properties such as rigidity, mass and temperature [19].

A common implementation of passive haptics is to recreate a real world tactile version of the VE that users will interact with such as the physical cockpit mockup suggested by Aslandere *et al.* Joyce and Robinson investigated user interactions with a passive haptics setup they called the “Rapidly Configurable Research Cockpit”, which was used to simulate cockpits for spacecraft and aircraft [31]. This setup consisted of a rectangular panel with 3D printed buttons attached, with users interacting with it with and without this passive haptics setup, being measured on task performance

throughput as well as reported presence and fatigue. The results from this study concluded that including passive haptics for feedback in VR simulations improved the users' feeling of presence, which in turn reduced training duration and improved overall task performance.

Insko conducted a study to measure user presence with passive haptics in two different VEs, the first had users stand on the edge of a board overlooking a pit below with a real elevated wooden board for haptic feedback [33]. The second VE had users navigate a maze with passive haptics objects made out of polystyrene bricks and cardboard. The results from the first VE with the pit showed that users felt an improved sense of presence with the haptic feedback, with even a significant rise in heart rate reported, while the second VE with the maze investigated their feeling of presence, as well as training transfer. Users who were initially trained with the passive haptics setup displayed faster navigation times and fewer collisions than those trained without the haptic feedback, showing that spatial knowledge transfer was better when using haptic feedback.

Cheng *et al.* developed a "Sparse Haptic Proxy", which was a passive haptics setup that consisted of a sparse set of primitive geometric shapes arranged in a section of a sphere, with a range of 120° [78]. Instead of the usual passive haptics scenario of modelling the real world setup to mimic the VE exactly, this setup was designed to provide haptic feedback for many different VEs varying in size and shape. For this study the VEs were a regular table with objects and a spaceship cockpit, the idea being to use a position remapping technique called Haptic Retargeting that manipulates the user's hand-eye coordination while reaching out to the target in the VE. The software could redirect the user's hand to a physical proxy of the target on the Sparse Haptic Proxy setup, despite this not correlating to a one-to-one mapping of position in the VE and real world setup. The scenario enabled users to perform actions that were common in many virtual experiences, with users reporting that they preferred less redirection in their movements when moving toward targets in the VE.

Han *et al.* also investigated the remapping techniques of Translational Shift and Interpolated Reach, the focus being on using one single passive haptic object to represent many virtual objects and altering user position perceptions when reaching out to these virtual objects [79]. They noted that unless a tactile Passive Haptic setup is custom-made to match a VE, matching physical and virtual objects perfectly is limited. The remapping techniques stem from studies that indicated that a perfect physical representation of a virtual object is not completely essential to maximise

the sense of presence for users interacting with a VE. Studies have shown that although not perfect, the visual sense can override the proprioceptive senses (sense of body position), and in the case of physical passive haptic objects not perfectly representing the corresponding virtual objects, allows for some spatial warping in the virtual space to go unnoticed. Han *et al.* note that there will be cases where the mismatch between the physical and virtual object would be large, to the extent that these techniques no longer become viable for realistic interactions. In their study employing these remapping techniques with users reaching out to virtual objects and their corresponding real world object, it was noted that, especially when using the Interpolated Reach technique, reach time and errors increased significantly after an observed limit to the distance offset was reached.

Zenner and Krüger created Shifty, a dynamic passive haptic feedback device that can dynamically change its rotational inertia to give users the feeling of different weights and forms [30]. It does this by using a motor driven linear actuator inside a hollow cylinder to move a weight along its length. When the device is held, this allows the user to perceive the object changing over time with regards to its mass profile, such as an extending telescope, and also to perceive objects with a fixed mass corresponding to the internal weight's position, such as a cube at the end of a handle. Zenner and Krüger showed that Shifty could be used as a VR controller to greatly enhance a user's perception of mass and inertia in a VE.

While the haptic retargeting techniques mentioned do offer a decent alternative to providing haptic feedback, it was observed that users produce more errors when they are required to move larger distances, preferring shorter distances when using these techniques, thus limiting their use. From the other passive haptics studies mentioned, it appears as though a one-to-one mapping from the VE to the haptic display is the most ideal situation. Users prefer these setups, with the results showing that training and task performance are improved using these one-to-one passive haptic displays. However, they still have limitations as they are static and would be expensive to build for each unique VE, the need to be designed to fit a display accurately, limiting their variations, with a much-needed dynamic element being required for these displays to fit changing VEs.

2.5 Encountered-Type Haptic Devices

Many of the studies on haptics mention the importance of McNeely's proposal of "Robotic Graphics", the limitations of VR with users passing through virtual objects

emphasising the need for realistic haptic feedback [13]. McNeely proposed the Robotic Shape Display (RSD), where a robot would simulate hard immovable objects, as seen in a VE, by moving a corresponding shape to the correct position and locking its brakes, with viscosity and elasticity also being simulated this way. This is called *encountered-type haptics* as the RSD waits for the user to “encounter” its objects. McNeely stated that this display would work best in VEs where objects of fixed size appear repeatedly, such as the case of layouts with many buttons, knobs and switches. The RSD requires the robot to track users quickly and accurately, which would make an ideal implementation require expensive equipment to implement. Errors in robot movement or slow speeds could also result in users getting hurt due to collisions, with the solution requiring safety systems to protect users. McNeely proposes that the robots used should only exert enough force for the RSD purposes and that the objects presented for interaction should be made from light material such as polystyrene. Software for the VE should employ accident-avoiding techniques, but must only be regarded as a secondary line of defense, as software can be unreliable.

RSDs, also known as Encountered-Type Haptic Displays (ETHDs), come in a variety of forms, with Mercado *et al.* categorising them as grounded and ungrounded types [20]. Grounded type ETHDs are fixed to the floor or a base, and can be robotic arms or fixed platforms which are constrained to a limited workspace that users can explore and interact with. The actuators of these grounded types will move accordingly to encounter a user interaction with a virtual object to provide haptic feedback. Ungrounded ETHDs comprise of Unmanned Air Vehicles (UAVs), such as drones, mobile platforms that move on surfaces, and wearables that are usually attached to the user’s hand. These are unconstrained and offer a potentially limitless workspace to interact with.

Yokokohji *et al.* implemented an ETHD called the What You can See Is What You can Feel (WYSIWYF) display [25]. They noted that McNeely classified haptic displays as worn-type (e.g. VR gloves), held-type (e.g. VR game controllers) and encountered-type, with the latter not requiring the user to have the haptic device on their body at all times [13]. They adopted the encountered-type approach and used a Puma 560 robot to provide the haptic feedback for their VE. This robot had a single square panel that had its orientation changed based on how the user decided to interact with a virtual cube. The square panel was repositioned so that the user could interact with all sides of the cube, the system operating in two modes, surface display and admittance display mode. During surface display mode, the system tracks the user’s motions and places the square panel at the appropriate location, waiting for the user to ‘encounter’ it, after which it switches to admittance display

mode, and responds to the forces exerted by the user on the panel to enable the perception of a solid immovable object. Yokokohji *et al.* noted that even though the system worked as intended, the Puma 560 robot could not keep up with the user's quick or erratic motions, and implied that careful path planning should reduce collisions with the user. Another limitation was that the device could not supply the user with any shape to interact with, which meant that they would be limited to a few fixed objects such as buttons, knobs, edges and surfaces.

Gruenbaum *et al.* implemented an ETHD system that was more in line with McNeely's proposal, that used a robot arm, the four DOF Adept 1 Manipulator, to track users and present them with objects to interact with in a just-in-time, only-as-needed basis [24]. This system was different to the one developed by Yokokohji *et al.*, as the robot arm had a rotating turret at the end with four different types of switches, with the corresponding VE being a control panel with many of these switches repeated at different locations. The system showed that it could add to the level of immersion in a VE by allowing users to reach out and touch real objects. Gruenbaum *et al.* state that the quality of haptic devices are determined by three factors: the viscosity felt when not interacting with a virtual object, the spring constant felt when interacting with a rigid virtual object, and the reaction time of the system. They note that the level of realism this system was able to provide was not sufficient for a VR training system, as the user is easily able to move faster than the robot arm can track, with the user moving slowly to match the robot's speed feeling unnatural. They emphasise that a quicker robot would be able to allow the user to move faster and more naturally, and that one with greater degrees of freedom would also allow for improved orientation of the objects, resulting in a more flexible simulation.

Yafune and Yokokohji created a system that could virtually simulate a full ETHD control panel system, similar to the one physically built by Gruenbaum *et al.*, to enable a system to be evaluated before building a physical prototype [24, 46]. They also presented a motion planning algorithm for the ETHD so that it could be encountered by the user correctly upon interacting with a virtual switch and avoiding user collisions at all other times, as was emphasised by McNeely [13]. The motion planning algorithm also reduces the duty of the ETHD motion, the proposed solution being verified by numerical simulations. Yafune and Yokokohji simulated the Mitsubishi PA10 robot arm as the ETHD and noted that the planned motion was still too fast for it or other existing robot arms at the time to keep up with, and that further improvements were needed to implement this algorithm in an actual system.

Araujo *et al.* implemented an ETHD system called Snake Charmer, which also allowed users to interact with objects such as switches and knobs, as was done in previous examples [26]. Snake Charmer also presented objects with different textures and active endpoints, such as airflow from a fan, and a temperature element for users to interact with, with users being able to grab the objects presented and change their position. The system could also simulate moving objects, such as a snake ‘attacking’ the user, the robot arm used as the ETHD device being the Robai Cyton Gamma 300, a smaller commodity robotic arm than the previous arms mentioned. The performance of this system was measured by how quickly the arm could reposition itself when users moved to interact with different objects, this being affected by the system latency, arm speed and distance to travel. Araujo *et al.* found that the maximum velocity of the arm was 0.9m/s for distances up to 0.3m and slower for small distances. While the Robai Cyton Gamma 300 proved to provide a good user experience for the simulations created by Araujo *et al.*, they do note that as it was a commodity robot arm, it had limits on velocity and spatial resolution. The arm would also bend if the user pushed too hard on it, which is not ideal to simulate solid immovable objects.

The previously mentioned examples of ETHD implementations were all grounded devices, their the maximum reach being the volume limits of the real world workspace and the corresponding portion of the VE that can be interacted with. Studies have been conducted on using aerial drones as ungrounded ETHDs, which could potentially provide an unlimited workspace to interact with. Yamaguchi *et al.* had users hold a sword-like grasping object to interact with a Parrot AR Drone 2.0 quadcopter, which had a flat piece of paper hanging off it as an end effector to provide the haptic feedback, and was able to provide a weak but perceptible force [41]. Abdullah *et al.* improved on this idea with their HapticDrone setup, and used the same drone with accurate force control via its upward and downward thrust to render the perception of stiffness and weight [27]. The forces achieved in this study were much higher with the maximum force recorded at 2.97N, this being equivalent to the weight of a filled soda can. While the drone solution potentially provides a much larger workspace to interact with, it does have a few shortcomings, with movement accuracy and agility being important performance factors for ETHDs. Abdullah *et al.* found that the drone struggled to quickly accelerate in a new direction whenever users changed movement direction suddenly. The drone also only provides forces in three DOF, limiting orientation of virtual objects, and its operation time being limited by its battery life.

HapticBots by Suzuki *et al.* are ungrounded mobile platform ETHDs that are

compact, each being $4.7\text{cm} \times 4.7\text{cm} \times 8\text{cm}$ in size and weighing 135g, and can move within a 2D plane of $55\text{cm} \times 55\text{cm}$ [80]. By raising the top shelf of a HapticBot, it can extend its reach into the third dimension from 8-32cm in height. It can move at a maximum speed of 0.24m/s on the working space plane and extend its shelf vertically at 0.028m/s. HapticBots can provide multiple simultaneous touch points by controlling multiple robots at the same time, and as they are small and light, the forces provided are small and the robots can potentially be knocked over. The speed of the robots is also still too slow, and user movements can easily outpace them before they are able to move to their next positions to provide haptic feedback at the new positions.

The size and weight of mechanical equipment used to deliver haptic feedback to users are usually proportional to the forces they can deliver, as well as their cost, which tend to constrain the best devices for the task to arcades and research laboratories. Quigley *et al.* surveyed costs of robot arms in 2011 and found that most robot arms used for research purposes were all in excess of \$100,000 USD [81]. When looking at low-cost arms, they found the KUKA youBot to be the cheapest at \$3500 USD. Lu *et al.* also conducted a survey of robot arms used in research in 2012 [82]. They found that even low cost industrial robots are still in the price range of €17,000 to €27,000. They also found that low-cost arms for educational purposes were in the range of €70 to €1,285 but had poor precision and repeatability.

Human actuation was proposed by researchers as a viable alternative to mechanical actuation, which could provide similar effects at a fraction of the cost. Cheng *et al.* created a VR system called TurkDeck with various attachments to provide haptic feedback, the users being able to manipulate the environment, and the VR being able to change via human workers who operate these as the user interacts with them [83]. Users responded with high ratings for the realism and immersion of this system, with Cheng *et al.* further exploring this idea with Mutual Turk, which had two users interacting with different but synchronised virtual experiences [84]. Shared attachments allow users to experience forces in both environments at the same time, for example, in one VE, the user is fishing and reeling in a catch, and in the other VE, the user is flying a kite in stormy weather. The strong forces exerted by the users on each other make the scene feel genuinely realistic without the need for machinery, this method of mutual human actuation also scoring highly for realism and immersion in the system.

Encountered-Type Haptics bring the much needed dynamic element for passive haptics to provide effective feedback in VEs, with different implementations providing varying

degrees of effectiveness. Human actuation is not very practical for most situations, with drones providing more area to explore but being limited in speed and force. Robot arms vary in speed, force and reach depending on the cost of these devices, with many studies also noting that these robot arms are not able to keep up with normal human motions, a problem that also applies to ungrounded ETHDs. If ideal specifications for ETHD speed is to be determined, knowledge of the range of normal human movement speed needs to first be considered.

2.6 Desired Speed Capabilities of Encountered-Type Haptic Devices

Effective ETHDs need to track users quickly, provide adequate counterforce to their interactions and a wide area for them to explore. For this study the area to explore will be fixed and will be adequate for research purposes, the counterforce being taken care of by virtue of the proposed ETHD being designed to be a tabletop device that operated on the XY plane parallel to the table surface. This design ensured solid immovable objects as users would not be able to move them along the Z-axis, which leaves the speed of the desired ETHD to be determined.

McNeely stated that RSDs should be able to track users quickly and accurately, but did not give the exact data for the tracking speed [13]. Tracking user speed could refer to the entire body or a single body part, the most common in VR applications being the human hand, which will also be the case in this study. Therefore, knowledge of the range of velocities and accelerations produced by the human hand is needed to meet McNeely's suggestions before deciding on the targeted speed capabilities of the proposed ETHD for this study.

Many studies centered on human hand movements have been focused on data that was appropriate to very specific movements, with older methods requiring people to physically move objects. Nagasaki recorded the angular velocity and acceleration of subjects' arms as they moved a rotating handle, while Flash and Hogan asked subjects to move a hinge-like system that measured the movement via a potentiometer [85,86]. Movements in a straight line revealed an approximate maximum velocity slightly above 0.75m/s and an approximate maximum acceleration of 4.2m/s² from graphical plots supplied.

Atkeson and Hollerbach used the Selspot system to analyse human movements, this being an early version of the infrared Light-Emitting Diode (LED) and camera

technology that is now widely used to capture depth information [87]. Subjects were asked to raise their hands upwards in a sweeping motion, the graphical results indicating that the maximum tangential velocity of the wrist goes up to 1.3m/s.

The Microsoft Kinect has become popular to use for research on hand gesture recognition and experiments that require depth capture in general [88]. Chen *et al.* investigated the recognition of dynamic hand gestures using the Kinect and an ASUS Xtion sensor [51]. They do not provide any captured velocity data, but do state that their system should only recognise a dynamic gesture if the velocity of the hand motion is above 0.3m/s for swipe gestures and above 0.15m/s for waving gestures. Hincapié-Ramos *et al.* investigated fatigue caused by mid-air interactions using the Kinect, with the captured velocity data not being given [52]. However, one of the mid-air gestures that subjects were required to perform was a side-to-side swipe, which they defined to be valid at velocities above 0.5m/s.

Elgendi *et al.* directly studied the speed of arm movements of healthy subjects using the Kinect, with each subject being required to do five different arm movements at “slow”, “normal” and “fast” speeds [56]. The speeds of the shoulder, elbow, wrist and hand were recorded, the latter being shown to move the fastest. Graphical representation of the recorded data showed that the average velocity of the hand for fast motions was approximately 5.0m/s, and that the average acceleration of the hand was just under 150.0m/s².

DeGoede *et al.* studied how subjects reacted when put in a situation where they had to use their hands to protect their heads and torso [55]. Subjects were first asked to raise their hands as fast as possible from thigh to shoulder, then to do the same, but in this instance to stop a swinging pendulum, which reached the subjects with an impact velocity of 1.8m/s, requiring quick actions. The movements were measured using an OPTOTRAK system which tracked infrared LEDs that were placed on the subjects, graphical representation of the data indicating that the maximum hand velocity recorded was slightly under 3.0m/s and maximum acceleration was under 30.0m/s².

A study by van Meulen *et al.* made use of a single inertial sensor to measure lower arm movements, as they wanted a system with fewer sensors that would be suitable to assess human body movements in clinical and daily life situations [53]. The subjects were seated and required to perform different prescribed movements such as extending one arm and bringing it back to the chest, graphical representation of the data giving a maximum velocity of approximately 0.8m/s.

It can be inferred from the studies where users are asked to move as fast as possible that humans can move their hands very quickly. The work by Elgendi *et al.* and DeGoede *et al.* present high velocities, from 3.0m/s to 5.0m/s, but their acceleration measurements of 30.0m/s² to 150.0m/s² are extremely high, even faster than a Bugatti Veyron, which has an average acceleration (from 0km/h to 100km/h) of 11.29m/s² [54–56]. These acceleration measurements may not be completely reliable and were ignored for the purposes of this study. When choosing components to build a tracking device, the faster performing components will usually be more expensive. As this project did not require subjects to move as fast as they possibly can, the velocity tracking requirements were reduced to allow for tracking at more relaxed speeds, but not too slow.

Gesture based studies usually have a minimum velocity requirement to begin tracking of a valid gesture, the work by Chen *et al.* and Hincapié-Ramos *et al.* have similar minimum velocity requirements, the measured data of more relaxed movements from the work by van Meulen *et al.* correlating with these velocities [51–53]. Therefore, based on this data, it was decided that the movements to be tracked would be of a more relaxed nature, and that the components should track at a minimum top speed of 0.5m/s for an acceptable feeling of realism when interacting with the ETHD. Ideally the device should track at any possible speed that a human arm is capable of, but due to cost constraints, 1m/s should be acceptable, and anything faster than this would be favourable. Acceleration of the device should be as fast as possible, but the higher the acceleration required, the more expensive the system becomes. As the ETHD area to explore for this study was not too wide, the recorded acceleration of 4.2m/s² by Flash and Hogan should suffice to meet the 1m/s velocity targeted for the ETHD to meet.

2.7 Hand Tracking in Virtual Reality

Interacting with objects in a VE can be achieved in many ways, the most common being to use controllers, as they are widely used in video games. The keyboard and mouse are also controllers, these being the default interaction devices for computers, and allow users to effectively interact with computers and gaming consoles on the applications they require control over.

However, these become more hardware that need to be managed, and require enough time to upskill before being able to operate with them effectively [89]. Using hands is one of the most natural ways to interact with the real world and operate these

controllers. In a completely virtual world that is designed to imitate reality, it could then be reasoned that using hands would be the most natural way to interact with it. Hand tracking is a solution that allows users to naturally interact with a VE with their hands, as they are instinctively inclined to interact as they would in real life, expecting the natural physical laws of the universe to remain consistent. VEs that are capable of accommodating these natural interactions improve the immersion and presence experienced by the user, and could possibly also contribute to improved task performance.

Extensive research has been done on hand tracking to enable the use of a user's hands as HCI devices, with VR gloves, such as the Manus Prime II motion capture glove and the Rutgers Master II-ND force feedback glove, being high quality VR interaction devices that also provide haptic feedback [72,90]. These types of gloves are expensive, being mainly used for research and industrial purposes, while HCI devices that capture hand movement data for use within VEs that are consumer-grade and more affordable include the P5 Glove, the Leap Motion Controller and Microsoft's Kinect [51,91,92]. The Microsoft Kinect and Leap Motion Controller are different to VR gloves as they enable natural user hand interactions without the need to wear additional hardware and allow an interaction with VEs in the most natural way possible, which increases the immersion and presence experienced [10]. However, the Kinect and the Leap Motion Controller are still additional hardware components to the VR setup.

The Oculus Quest headset improves on the hand tracking concept by reducing the number of hardware components needed, the four fisheye monochrome cameras on the exterior use image capture in conjunction with neural networks to recognise the user's hand. The Quest's hand tracking software then uses this data to construct virtual representations of the user's hands within the VE, and was the first VR headset that offered this hand tracking capability without requiring additional hardware at the time of conducting the study [93]. The Quest 1 was also affordably priced compared to other potential VR hand tracking setups such as the HTC Vive and Leap Motion Controller, and was therefore an attractive solution with regards to hand tracking in VR for this study.

2.8 Chapter Summary

This chapter presented a literature review on various aspects of VR, as summarised in Table 2.1.

Table 2.1: Summary of literature review

Category	Summary
VR and Training	VR is a much more effective tool for training simulations compared to conventional methods such as training manuals, videos and presentations. Study participants who were trained on VR had improved training transfer and task completion. VR can expose trainees to a variety of scenarios, including those that would be too dangerous in real life.
Haptic Feedback in VR	Haptic feedback improves the realism of VR by adding the touch component. Various methods of delivering haptic feedback to the user are available, such as the use of VR gloves, vibrations, magnets, air vortices and ultrasound. These allow users to pass through virtual objects, which is not realistic.
Passive Haptics	Passive haptics is one of the most realistic forms of haptic feedback by allowing users to interact with solid real world objects that correspond to the virtual objects that users see. Users can feel the shape and textures of these objects as well as physical properties such as rigidity, mass and temperature. However, passive haptic objects are limited to static locations.
Encountered-type Haptics	Encountered-type haptics enable passive haptic objects to be positioned dynamically for the user to have a richer experience with the use of ETHDs. Different ETHD implementations vary in speed, force, reach and cost, and are in general not capable of keeping up with quick/erratic human movements.
Desired Speed Capabilities of Encountered-Type Haptic Devices	ETHDs are required to keep up with quick movements to be able to deliver a realistic VR experience. Studies on human hand movements with mechanical setups, the Microsoft Kinect and the OPTOTRAK, indicate that an ETHD should target a speed of 1m/s and an acceleration of 4.2m/s^2 to be able to keep up with average user movements for realistic/seamless haptic feedback.

Table 2.1 – continued from previous page

Category	Summary
Hand Tracking in Virtual Reality	Hand tracking in VR is an attractive solution that provides users with natural interactions as no hardware needs to be worn, e.g. gloves. The Microsoft Kinect and Leap Motion Controller provide hand tracking but require extra hardware to be set up. The Oculus Quest VR headset was determined to be an appropriate choice for this study due to it not needing additional hardware for hand tracking, and its price.

Studies indicate that optimal haptic feedback is provided to the user in VR when an encountered-type haptics setup supplements the experience and can keep up with human movements. Realistic and optimal haptic feedback can greatly improve a user's task performance, which would be beneficial for this study. An ETHD that can reach speeds of at least 1m/s to provide quick haptic feedback is required for this study, complemented by an accurate hand tracking solution that will allow users to have a natural and realistic experience.

The next chapter will discuss the design and implementation of the *Fast ETHD* system that was built for this study. The discussions from this chapter were used to determine the design requirements that the *Fast ETHD* system needed to provide the user with an optimal experience, and had a direct influence on the components chosen to implement the final system.

Chapter 3

The Fast ETHD System

This chapter reviews the *Fast ETHD* system that was used in the experiments for this study, and outlines the design requirements needed and the design decisions made to meet them. The different components of the system and how they communicate are given, as well as their respective costs. The system features and operation of the system are reviewed, and its performance is discussed to establish how it met the design criteria and operated for different speed profiles.

3.1 Introduction

As a goal of this study is to investigate how Encountered-Type Haptic Display (ETHD) speed affects immersion, presence, User Experience (UX) and task performance, an ETHD system was required to answer the research questions. The final ETHD system designed was named the *Fast ETHD* system. This chapter reviews the system's design requirements, the final system and its constituent components, the design decisions made, and its performance.

3.2 Design Requirements

The ETHD system had to meet various quality attributes required as discussed in Chapter 2. The design requirements are listed as follows:

Design Requirements

DR1-SPEED

The ETHD should be able to track a user's hand at a fast enough rate so that they do not experience too much latency. The speed of the rig should at least be capable of reaching speeds of 1m/s as determined in Section 2.6.

DR2-SAFETY

The ETHD needs to be safe so that users have zero to minimal risk of being injured by the ETHD when it is in motion.

DR3-ACCURACY

The ETHD needs to be accurate so that the positions of buttons on the ETHD align to the positions of the buttons in the VR scene.

DR4-RESPONSIVENESS

Button clicks should feel responsive and click events should trigger actions immediately.

DR5-IMMERSION

The virtual environments that the player will interact with should put the player at ease and immerse the player so that they can focus on the tasks required for the experiments.

DR6-DATA-CAPTURE

Data capturing should be accurate so that the analysis on the data can be trusted.

3.3 System Components

When a user wants to click on a button in the Virtual Environment (VE), the new virtual button target position, along with the user fingertip position, is sent from the Virtual Reality (VR) application to another application running on a

laptop. The latter application will take this information and convert it into code for the new position that the rig needs to move to in order to align the virtual and real buttons, resulting in haptic feedback to the user. This code is sent to a microcontroller that will move the motors connected to the linear actuators of the rig to move a button panel attached to the rig's carriage. The *Fast ETHD* system is shown in Figure 3.1 and consists of a VR headset with the *VR Test* user application, Computer Numeric Control (CNC) rig with control electronics and laptop with the *QuestG2CoreBridge* application, while the system interactions can be seen in Figure 3.2. The items reviewed regarding the system were the CNC rig, Arduino Due *g2core* motor controller, button panel, *QuestG2CoreBridge* Java application, Oculus Quest headset, *VR Test* VR application, communications, lighting, proximity sensors, 3D button models, emergency stop button, and the table platform that the system is placed on.



Figure 3.1: The *Fast ETHD* system used for the experiments of this study.

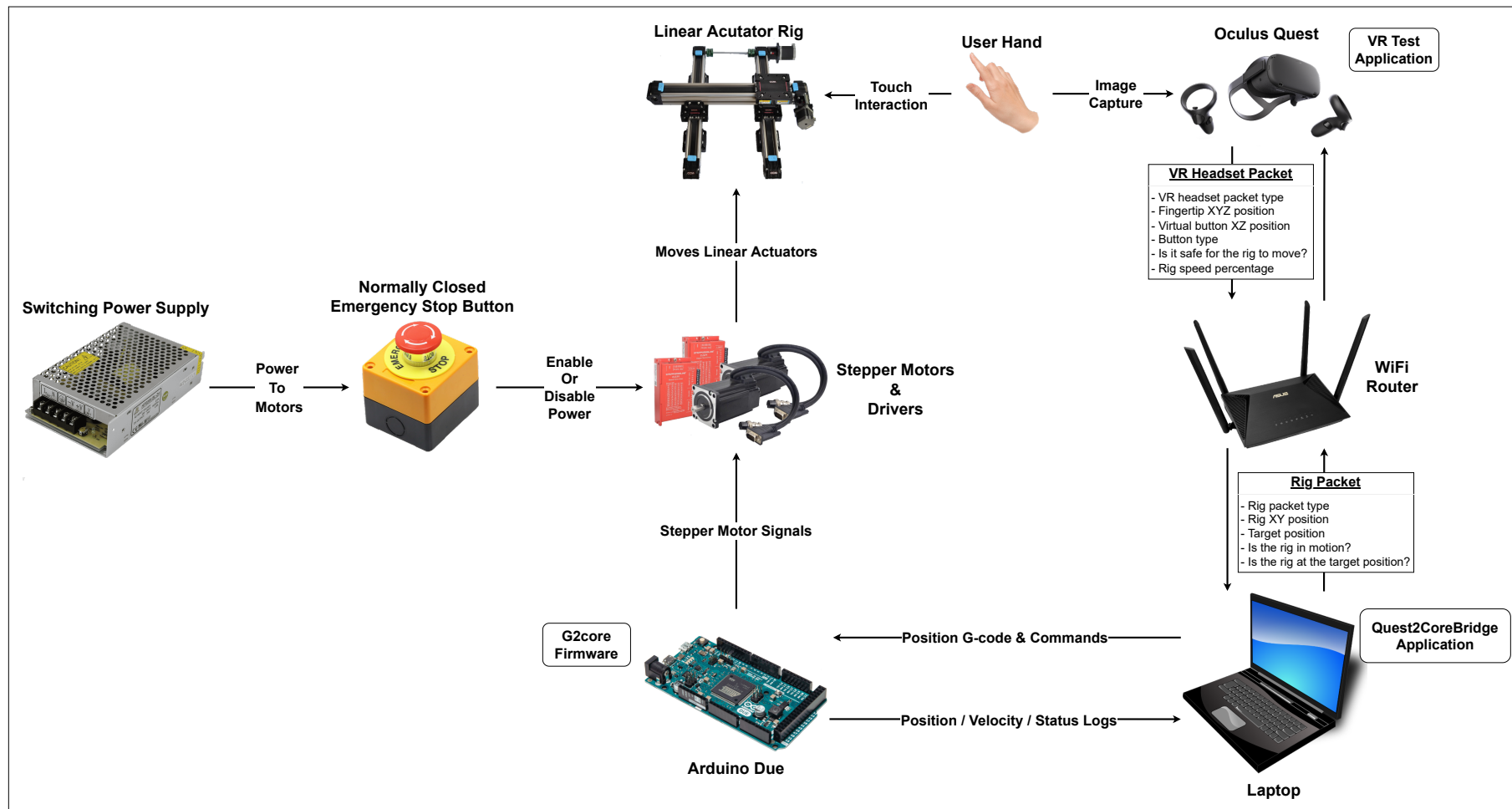


Figure 3.2: System overview.

3.3.1 Encountered-Type Haptic Display CNC Rig

The ETHD rig was built as a 2D CNC XY H-Gantry, with three belt-driven linear actuators being connected together, which resulted in a 2D workspace of $1m \times 1m$. Each axis was driven by a 2.0Nm NEMA23 stepper motor and its associated motor driver, which were powered by a 400W switching power supply (36V 11A). All these components were able to move the top layer carriage of the rig, onto which the button panel was attached, at speeds above 1m/s, which met the requirement for DR1-SPEED.

Belt-driven linear actuators were chosen over screw-driven linear actuators due to their superior speed properties. The CCMW40-06 linear actuators were chosen as these met the speed requirements of DR1-SPEED and the accuracy requirements of DR3-ACCURACY. Positioning repeatability of this product was able to achieve an accuracy of less than 0.05mm.

Stepper Online YE series NEMA23 2.0Nm closed-loop stepper motors and their associated CL57Y drivers were used to move the belts of the linear actuators. These motors were able to deliver a high enough torque to the linear actuators to enable them to move fast enough to meet DR1-SPEED. The motors were also able to change direction quickly which was necessary to reduce latency when tracking user movements, which could be quick and unpredictable.

The rig is required to stay in place for the entirety of an experiment, movement out of its initial position could result in a misalignment of the virtual and real objects on the rig, which could affect the results. The rig was placed on a rubber sheet to reduce any unwanted vibrations or movements due to momentum from the high-speed carriage movement, which stabilised it and ensured alignment of the virtual and real objects.

3.3.2 Arduino Due g2core Motor Controller

The *g2core* firmware was flashed onto an Arduino Due microcontroller board to control the position of the rig. G2core is a stepper motor based motion control firmware that is used for CNC applications such as 3D printers and laser cutters, and takes in G-code as input, which is a CNC programming language that is used to control motor movement and speed to move automated machines in specific trajectories [94]. These G-code instructions are processed by g2core in real time to

control motors for each axis to position the rig carriage.

Velocity, acceleration, jerk and up to 6th order motion derivatives (snap, crackle and pop) can be configured in g2core for the trajectory planning. This 6th order motion planning allows the motors to run smoother and cooler, and reduces machine vibration and resonance [95]. The motors can run optimally at high speed and positional accuracy, which is required for DR1-SPEED and DR3-ACCURACY. Potential configurations for maximum velocity (xvm and yvm) and jerk (xjm and yjm) were explored until the rig moved as fast and accurately as possible with no positional errors or vibrations.

The final configurations are $xvm = yvm = 75000mm/minute = 1.25m/s$ and $xjm = yjm = 10000mm/minute^3 \approx 46.296 \times 10^{-6}m/s^3$. This speed profile was considered to be the maximum of the rig and is referred to as the 100% speed profile. All other lower speed profiles are derived from this speed profile by maintaining the jerk configurations and changing the xvm and yvm configurations as percentages of the maximum. For example, if a 10% speed profile is required, the velocity configuration changes to $xvm = yvm = 75000mm/minute \times 0.1 = 0.125m/s$.

The Arduino Due microcontroller board houses a 32bit Atmel SAM3X8E ARM Cortex-M3 CPU that had the processing power to run g2core in real time. This board proved to be capable even when sending multiple G-code G0 position instructions in quick succession for stopping the carriage completely or changing directions. The board could be connected to a computer via USB cable, and the G-code commands sent to it over serial communications. A wiring diagram for the system components to the Arduino Due and a reference for the g2core pinouts can be found in Appendix A.

3.3.3 Button Panel

A cardboard pizza box was used to house the button panel, which was screwed onto the rig carriage in such a way that the centre of the carriage aligned with the centre of the button panel. The intention was to use this as a prototype and eventually replace it with a material for the housing that was more sturdy, such as perspex. However, the decision was made to keep the pizza box as it was light, easy to work with, cheap and easily replaceable, its light weight contributing a negligible weight load for the rig to move around. This also made it possible for the rig to move and change direction as fast as possible, with soft cardboard material also making it easier to cut holes to place the buttons and to change the button layouts quickly.

The buttons were a variety of standard plastic arcade machine buttons (Figure 3.3), and were all normally open momentary contact buttons that are available in circular, square and triangular shapes of different sizes and colours. All the buttons had a distinctive ‘click’ when pushed to give haptic and audible feedback to the user that the button had been pushed all the way in. These were used purely to provide haptic feedback and were not wired to the system (Figure 3.4).



Figure 3.3: The button control panel.

3.3.4 QuestG2CoreBridge Java Application

A custom software application called *QuestG2CoreBridge* was developed to primarily act as a bridge between VR applications and ETHDs to control and provide accurate haptic feedback to the user. This application can receive hand and target object

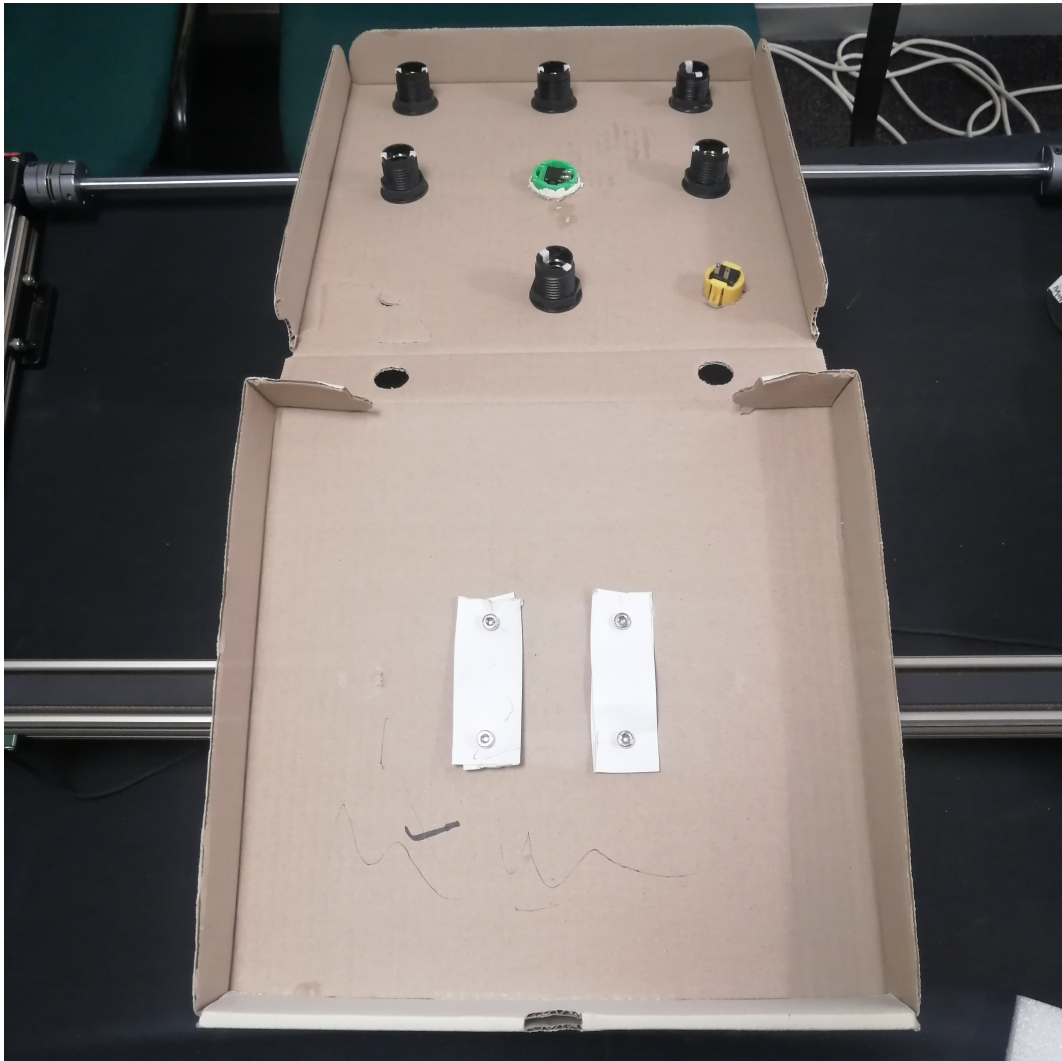


Figure 3.4: The button control panel when opened.

positions from the VR application, and convert them into G-code position and velocity configuration instructions. These instructions are then sent to the g2core firmware over serial communications to change the position of the rig's button panel to provide position-accurate haptic feedback. This application ran on a Dell G5 15 laptop which had an Intel Core i7-9750H hexacore CPU running at 2.60GHz and 16GB RAM. The *QuestG2CoreBridge* application ran on the Windows 10 Home 64bit operating system and was developed in Java.

The *QuestG2CoreBridge* application interface can be used to initialise the rig position for proper alignment during calibration to make sure that it only moves after proper calibration has been completed. This application displays all logs from the g2core firmware including position, velocity and alarm status data. It processes virtual finger and virtual target position data received from the VR application and converts

it into physical position data that the g2core firmware understands for the rig to move to. It also sends back the live physical rig position and velocity data to the *VR Test* application. An animated visual display shows representations of the virtual finger and button target positions and the physical rig position, with a screenshot of the application presented in Figure 3.5.

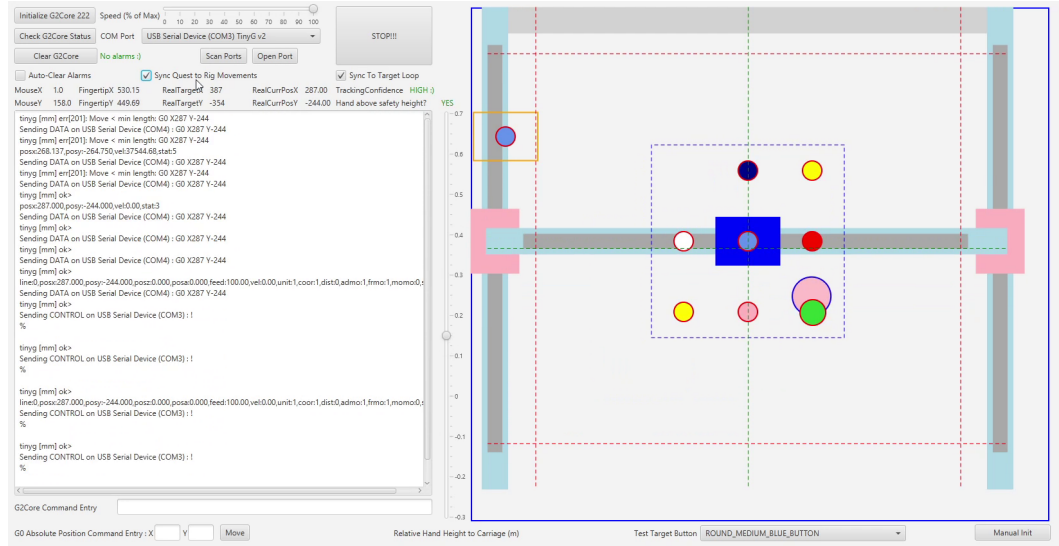


Figure 3.5: The QuestG2CoreBridge application interface.

Speed profile changes can be manually set in this application or when it receives a request from the *VR Test* application, the speed profile being a percentage of the maximum speed defined in Section 3.3.2. The new speed limit is calculated based on this and the commands are sent to the g2core firmware to action, with the data on the instantaneous velocities for different speed profiles also being captured by this application into text files for data analysis.

A custom communications protocol was created to enable the position data between the VR and *QuestG2CoreBridge* applications to be clearly understood. Packets for this information were sent over User Datagram Protocol (UDP), with both of these applications needing to be on the same subnet and broadcast their IP address on startup to know the source and destination of packets. These packets are in JavaScript Object Notation (JSON) format to be platform and programming language independent, with each packet having a unique identifier that gets incremented for each new message sent. Only messages with the most recent identifiers are processed to reduce latency and for the rig to move to the most recent position required, this being done to meet DR1-SPEED, with the packet schemas being listed below:

Rig Packet

Integer messageId
 String message
 HapticRigPacketType hapticRigPacketType
 Float x
 Float y
 Float z
 Boolean rigInMotion
 Boolean rigAtTarget
 Float targetX
 Float targetY

VR Headset Packet

Integer messageId
 String message
 VrHeadsetPacketType vrHeadsetPacketType
 Float fingertipX
 Float fingertipY
 Float fingertipZ
 Float buttonX
 Float buttonZ
 TrackingConfidence trackingConfidence
 ButtonType buttonType
 Boolean rigSafeToMove
 Integer rigSpeedPercentage

3.3.5 Oculus Quest Headset

The Oculus Quest (first version) was chosen as the VR headset to be used in this study, as it has minimal hardware requirements in that only the headset is needed. This version has a display refresh rate of 72Hz, giving the user a smooth viewing experience, which increases immersion and presence and meeting DR5-IMMERSION. It has hand tracking built-in, courtesy of the *MEgATrack* system, with a sampling rate of 30Hz, its tracking rate being noticeably lower than some other solutions, such as the Leap Motion Controller, which operates at 120Hz [93, 96]. The Quest's hand tracking feature is smooth and accurate in practise, and acceptable for use in this study, with adequate lighting being required for it to accurately track hand

movements. The Quest’s high-accuracy controllers have sub-millimetre precision, which are used for initial calibration to align the virtual world coordinate system to the real world coordinate system of the button panel to meet DR3-ACCURACY.

The Quest 1 was also one of the more affordable headsets on the market at the time of purchase in February 2020, shortly before the Covid-19 pandemic restrictions were implemented in South Africa. At the time of writing this document, and during the time the experiments for this study were conducted in April 2021 and February 2022, the Quest 2 (also known as the Meta Quest 2) had already been on the market for a while, with improved visual display, hand tracking and price tag than the first version. Despite the Quest 2 being the preferred option at the time, the Quest 1 had already been purchased and its performance during pilot studies met all the requirements for the experiments in this study.

3.3.6 VR Test Application

The *VR Test* VR Android application for the Oculus Quest was developed for the user to interact with a virtual interface. This application was developed with the Unity engine and C# scripting, and is a heavily modified version of the *HandsInteractionTrainScene* from the sample framework provided by Oculus [97]. The VE of the application is a representation of a clear summer day, consisting of a green ground, blue sky and a central blue control panel to meet DR5-IMMERSION. The control panel is dynamic, can have different layouts for text and buttons, and be angled at 0° (parallel to the ground/table), 45° or 90° (perpendicular to the ground/table). The virtual button models for this experiment are modelled on the real buttons that are attached to the ETHD button panel. Pushing a virtual button all the way until the user feels that the physical button cannot be pushed in further results in a click sound effect being played to give the user audible feedback that the click has been registered by the software.

The dynamic layout mechanism of the control panel is modelled to be similar to the lifecycle of webpages, undergoing phases for initialisation, event handling and unloading of objects. This interface moves through ‘scenes’, for calibration of the virtual and physical height and rotational positions, inputs for dominant hand, gender and age choices, as well as the practise and proper test experiment sequences, the age entry scene being depicted in Figure 3.6.

The *VR Test* application captured dominant hand, gender and age data that is

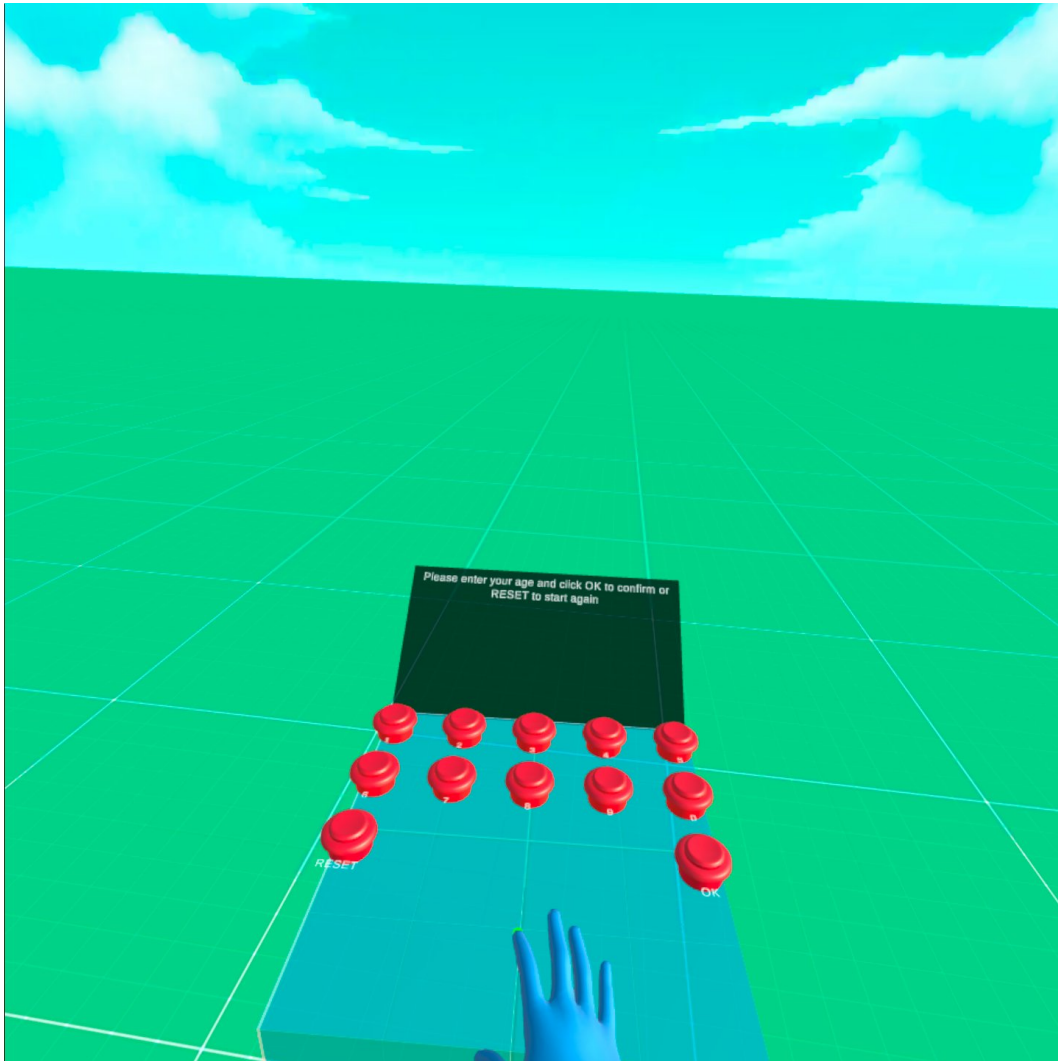


Figure 3.6: The *VR Test* application interface, with the age entry ‘scene’.

entered by the user into memory during their interaction, as well as data that was unique to the experiment sequences. Upon completion of the test, all relevant data in memory is saved to an XML file on the Quest’s on-board storage, and can be processed in statistical analysis software to meet DR6-DATA-CAPTURE. For this study, the R programming language was used as the tool for data analysis.

3.3.7 WiFi Communications

A TP-Link TL-WR840N 300Mbps WiFi Router was used to handle bidirectional network communications between the *VR Test* application on the Quest and the *QuestG2CoreBridge* application on the laptop, being used for a reliable and stable connection for the experiments. However, during pilot tests, the system was also

tested with the laptop or a cellphone being used as a WiFi Hotspot, and these also produced excellent results with the rate of packets sent being close to the Oculus Quest's display refresh rate of 72Hz.

3.3.8 Lighting

An LED spotlight was pointed at a wall opposite the rig to increase the brightness of the ambient lighting of the room, to achieve optimal hand tracking on the Quest.

3.3.9 Bricks / Table

The ETHD rig was placed on a table that was propped up on bricks so that users did not have to bend over too much to interact with the button control panel, the height of the surface from the ground being 95cm.

3.3.10 Emergency Stop Button

A normally closed non-momentary contact button was connected between the power supply and the motor drivers and used to immediately stop all power going to the motors in the case of an emergency arising.

3.3.11 Proximity Sensors

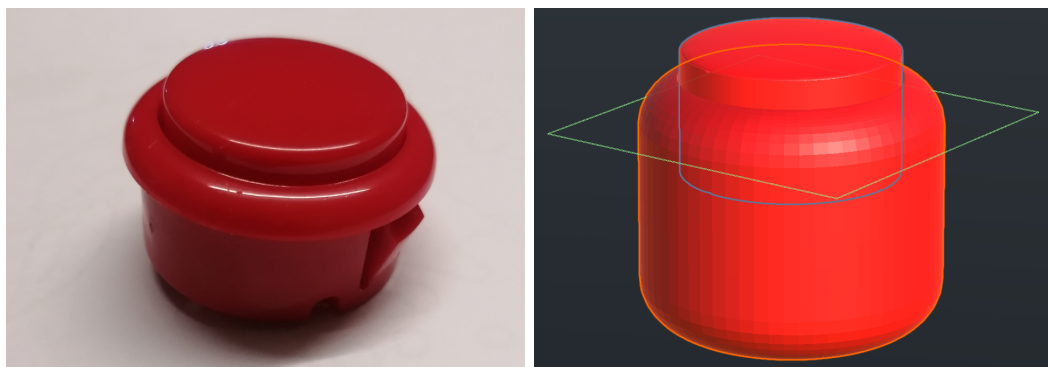
Two CCM GX-H8B inductive proximity sensors were attached to the linear actuators to determine the origin point of the rig on a repeatable basis, one being attached to the left of the upper linear actuator that moves along the X-axis (Figure 3.7), and the other to the forward end of the right linear actuator that moves along the Y-axis. These sensors were connected to the Arduino Due for the g2core firmware to determine the origin of the rig coordinate system.

3.3.12 Buttons and 3D Models

The real buttons on the rig control panel each had a 3D virtual model for the *VR Test* application (Figure 3.8), having been developed in Blender for use in Unity. Interacting with a real world push button consists of the user pushing down on the



Figure 3.7: The GX-H8B proximity sensor located on the left of the upper linear actuator.



(a) Real button used on the button panel

(b) The 3D button model of the real button

Figure 3.8: Real and 3D buttons.

button actuator, moving it into the button base until the circuit is closed and they can see the response to their button pressing action. In addition, they might also hear and feel a click which is usually part of the button design to give the user audible and haptic feedback that the circuit has closed. This design was replicated in these virtual models by separating the button base and button actuator (Figure 3.8b), the point where the click is felt being imitated by an invisible plane intersecting the button. For the response to occur, the user had to push their fingertip into the actuator of the virtual button until the fingertip position made contact with this plane, which then immediately initiated the intended action configured for that particular button instance to meet DR4-RESPONSIVENESS.

3.4 Costs

The costs for the *Fast ETHD* system are broken down in Table 3.1, with the total cost of the system being R53 057.83 (\$3609.36 USD), with the laptop accounting for approximately half due to it being a gaming-spec laptop. While the laptop was a high-end one to speed up development time, the *QuestG2CoreBridge* application running on it does not require such high specifications, with a lower spec laptop or PC, with at least one USB port and WiFi communications, being able to run this application adequately.

3.5 Design Decisions

There were a variety of components and approaches to choose from to build the *Fast ETHD* system, with the following design decisions made to achieve the requirements indicated in Section 3.2.

Table 3.1: Summary of system costs.

Category	Breakdown	Date	USD/ZAR rate	Price (ZAR)	Price (USD)
Linear actuators		19/08/2019	15.2987		
	Items			7955.32	520.00
	Shipping + Customs			2264.21	148.00
Motors + Drivers + Power Supply		13/01/2020	14.3615		
	Items			2632.18	183.28
	Shipping + Customs			1330.74	92.66
Ardunio Due		31/01/2020	14.607		
	Items			496.35	33.98
	Shipping + Customs			203.04	13.90
Oculus Quest		07/01/2020	14.2169		
	Items			10799.00	759.59
Assorted Buttons		02/10/2020	16.5919		
	Items + Shipping + Customs			1000.00	60.27
Laptop		10/12/2019	14.6728		
	Items			26377.00	1797.68
GRAND TOTAL				53057.83	3609.36

3.5.1 Motors

The motors chosen to move the rig were Stepper Online YE series NEMA23 bipolar stepper motors, as they were fast, accurate, provided adequate torque and already had a reputation of working well with the g2core CNC firmware. Three-phase stepper motors that provide higher torque could have been used, but as there is negligible load from the button panel, an excessively higher torque was not required. The added complexity of a third phase to drive the motors could possibly also have been a problem for the g2core firmware, with the simpler option of bipolar stepper motors being chosen.

3.5.2 Microcontrollers

There were many options for the microcontroller board and the firmware to control the motors, with two microcontroller setups being compared, the Arduino Uno flashed with the grbl CNC firmware and the Arduino Due flashed with the g2core CNC firmware. The Arduino Uno and grbl setup did not produce the performance and change response required for this study, as it could not move the motors at the minimum required speed of 1m/s to meet DR1-SPEED. This was possibly due to the lower clock speed of the Arduino Uno and the older, less capable grbl firmware. However, the Arduino Due and g2core setup was found to be capable of producing speeds well above what is required for DR1-SPEED, with the Arduino Due being used due to the larger memory and faster CPU requirements needed to run g2core, which is a follow-up to the grbl firmware.

3.5.3 Momentum

It became apparent that moving the rig's carriage from point to point with great speed resulted in a large amount of momentum, nudging the entire rig out of position when it was on a smooth surface such as wooden table. This was not ideal as the rig had to stay in position for its coordinate system and the virtual environment coordinate system to stay aligned. The smoothing of the motor movements by the g2core firmware helped but did not resolve this issue completely, with a relatively simple solution of placing the rig on a rubber mat fixing the issue. The friction of the rubber mat on the rig and the table below it was enough for the rig to stay in place, even with long-distance high-speed movements.

3.5.4 Button Model

There are a variety of approaches to modelling buttons in VR, one approach being to model the button clicking using the physics engine of Unity, where the button actuator is modelled with a spring constant for the most realistic movements and interactions. A caveat of this method is that adding too many buttons to a VR scene greatly reduces performance, to a point where the frame rate was no longer smooth. The *VR Test* application had to accommodate multiple buttons on screen at once due to the nature of the experiments. A much simpler button model was adopted that was used in the *HandsInteractionTrainScene* from the sample framework provided by Oculus, which removed the physics component and instead added a plane that intersected the button (Figure 3.8b) [97]. When the button actuator was pushed, a trigger was activated as the fingertip intersects the plane, the button actuator height corresponding to the fingertip position to allow the interaction to still be responsive and realistic. This approach performed much better, allowing the experience to be smooth with maximum frame rate, and enabled multiple buttons to be handled with ease, which meant that a limitation on the number of buttons onscreen at once became unnecessary.

3.5.5 Finger Model Accuracy

The hand model used for interactions in the Quest separates the fingers, the different bones of each finger and the fingertips, with only the fingertip of the index finger being considered. Simplifying the interactions to only use one fingertip resulted in there being many approaches to handling collisions with other objects. One way was to use the virtual hand model itself as an object with physics engine interactions so that any point on the fingertip could be used for interactions, another being to use a single position that approximates the fingertip. Due to the previous difficulties experienced using the physics engine with button interactions, the simpler single position fingertip approach was used. This also aligned to the ISO/TS 9241-411 multidirectional tapping task test that measures throughput of pointing devices with a clear singular point for interactions. The caveat of using this approach is that fingertip sizes will vary from person to person, and as the position is inside the fingertip, there is a discrepancy of a few millimetres when observing an interaction with an object. However, the interactions and calculations were simplified by using this approach, with users appearing to be quite happy with the button clicking actions in pilot tests.

3.5.6 Wiring

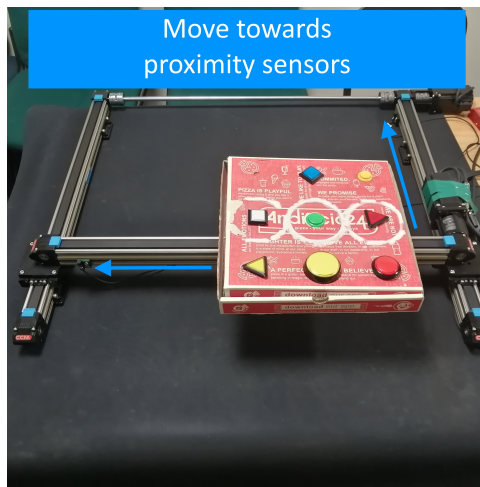
Due to time constraints, all wiring between the rig sensors, microcontroller board and motor drivers were done with jumper cables and a breadboard. All connections were tightened and some slack in the wiring for the proximity sensors and motors was allowed for. This resulted in repeatable operation of the *Fast ETHD* system.

3.5.7 Networking

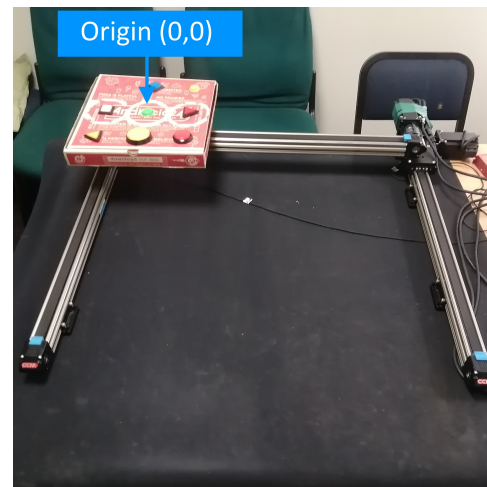
A typical client-server or peer-to-peer network has the components sending data to each other, that are encoded as binary packets on the sending component, and decoded back to its original form on the receiving component. These processes are called serialisation and deserialisation respectively, and usually works well when the sending and receiving components are developed using the same programming language or frameworks. In the case of the *Fast ETHD* system, the *VR Test* application on the Oculus Quest was developed in Unity which required C# for scripts, while the *QuestG2CoreBridge* application was developed in Java so that it could be platform independent. A normal binary serialisation and deserialisation process would not work very well, as Java and C# perform these processes very differently. Converting the data objects into JSON strings that were easily converted back to the original object due to the popularity of JSON in web-based applications was the chosen solution. While this approach is not as fast as binary serialisation, performance testing showed that the number of JSON packets exchanged was close to the maximum frame rate of 72Hz for the Quest which was ideal enough for handling position changes on the rig.

3.6 System Features and Operation

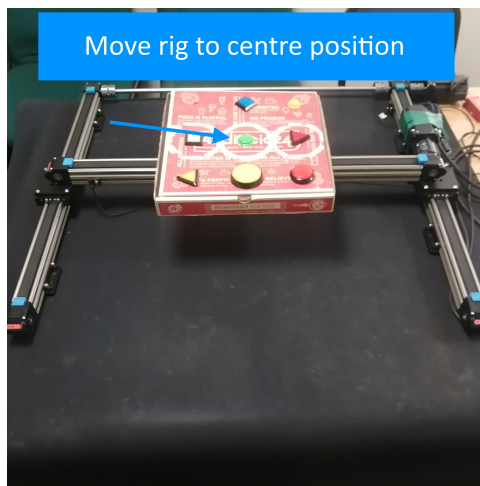
The final *Fast ETHD* system had a number of features that were designed to meet all design requirements, with some of the most important features being explained in this section. These were for the initialisation of the system, coordinate system alignment, hand tracking, application scenes, encountered-type haptic feedback, the *Safety Height* feature and the different control schemes for the *Fast ETHD* system.



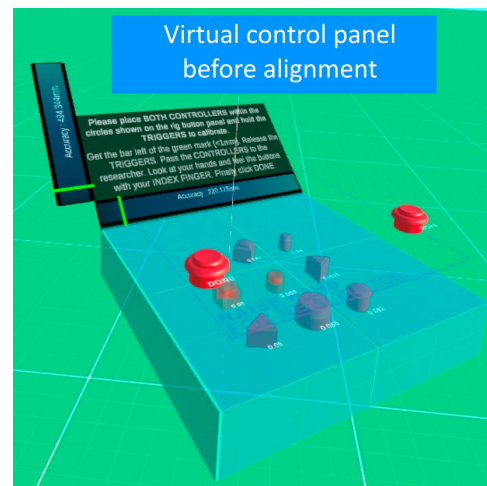
(a) Step 1



(b) Step 2



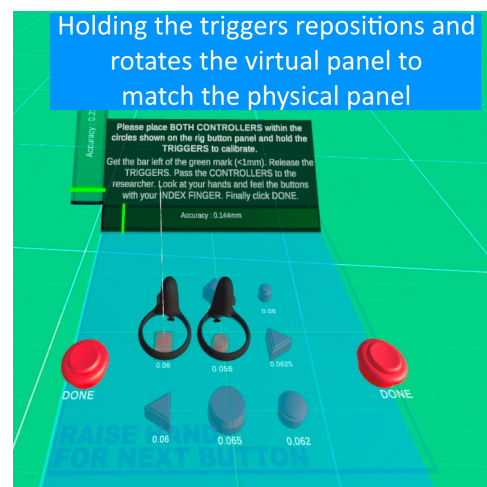
(c) Step 3



(d) Step 4



(e) Step 5



(f) Step 6

Figure 3.9: System initialisation process to align real and virtual world coordinate systems.

3.6.1 System Initialisation

The rig first needed to be initialised to a repeatable position that could be used as the origin for its coordinate system, with two proximity sensors, each mounted on the X and Y linear actuators, being used to determine its upper left corner. A function on the *QuestG2CoreBridge* application was used to initialise the system by sending the *G28.2 X0 Y0* command to the g2core firmware, which starts a homing cycle. This process first moves the carriage of the rig left until the *Xmin* position sensor is triggered, and then moves forwards until the *Ymin* position sensor is triggered. With the upper left corner of the rig determined as the origin, a second command moves the carriage to the centre position of the rig to start the alignment process, as depicted in Figure 3.9 for Steps 1-3.

3.6.2 Coordinate System Alignment

After the rig position was initialised, the *VR Test* application on the Quest could be started, which first shows the user the calibration scene. The user then places the Quest controllers within the left and centre rings on the physical button control panel and holds the triggers to start the alignment process. The virtual XYZ centre position is determined from the centre of the right controller within the centre control panel ring. The left controller in the left ring is used to determine the distance between the physical left and centre rings to match the expected distance between the virtual buttons as accurately as possible. Holding the controller triggers then starts a process similar to a bisection approximation method to rotate the virtual control panel until the virtual button centre positions match the centres of the controller positions. Two blue bars in the Quest view for X and Y accuracy assist the user to determine how accurate the alignment is, with sub-millimetre alignment for both X and Y components of the button and controller positions being the goal, depicted by a green marker. Once this level of accuracy was achieved, the rig and virtual button control panel coordinate systems were deemed to be aligned. The rig positions then accurately corresponds to hand tracking to give accurate haptic feedback, as depicted in Figure 3.9 for Steps 4-6.

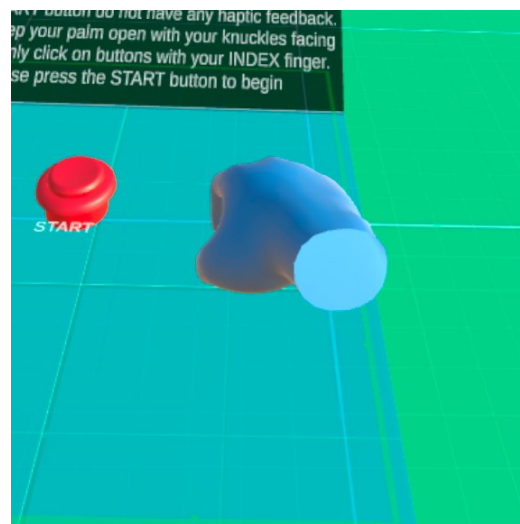
3.6.3 Hand Tracking

The user is able to view virtual blue representations of their hands in the *VR Test* application, and will choose their dominant hand to interact with the button control



(a) Palm open

(b) Index finger pointing outwards, all other fingers curled inwards



(c) Index finger pointing downwards

Figure 3.10: Examples of optimal (a), decent (b) and poor (c) hand tracking for different hand orientations.

panel during the normal process. While the user can click buttons with any finger, only the index finger will actually register the click to trigger an associated action, with the tip of the index finger position having a green sphere attached as a visual cue to the user to click on buttons with that point.

High confidence hand tracking requires good lighting conditions and for all of the user's fingers to be unobscured, with low confidence possibly arising from poor lighting, users obstructing the view of the Quest's cameras by blocking one hand with the other, holding the hand flat and perpendicular to the cameras so that no

individual fingers can be distinguished, or moving too fast.

Users were advised to keep their palm open and click only with their index finger by moving their entire hand downward to click as seen in Figure 3.10a. This was not natural to participants, as many tried to click with the usual pointing gesture of only the index finger pointed outward and all other fingers curled inwards as seen in Figure 3.10b. This resulted in decent hand tracking, except when users tried to tilt their hand so that they could point directly downward into the button, which resulted in poor hand tracking as the fingers could not be seen. The resulting virtual hand seen in-app was then incorrect, as the fingers curled incorrectly or were completely hidden as seen in Figure 3.10c, and sometimes resulted in the hand disappearing completely due to the low tracking confidence. When these types of errors occurred, button clicks did not register, which resulted in the user trying to click on the button multiple times until it finally registered the click. This was the main hand gesture observed with hand tracking problems, with a few individuals also trying to interact with the buttons in very unique ways with varying degrees of hand tracking confidence.

3.6.4 Scenes

The interface of the *VR Test* application can be configured to have multiple scenes that are presented to the user sequentially, which all follow a Model-View-Controller pattern with phases for initialisation, event handling and unloading of objects, similar to the life cycle of webpages. The application moved through various scenes for user help text, data input or training, with some of the common scenes presented being used to adjust height calibration, as well as to input dominant hand, gender and age choices, and the experiment sequences. These scenes all have different button layouts and help text, with the user being given the choices of “Right” and “Left” for the dominant hand choice scene. For the gender choice scene, the options of “Male”, “Female” and “Choose not to say” were available to select. Buttons labelled from zero to nine were shown for the age input scene, with a “Reset” button to erase what had been entered in case of a mistake, and an “OK” button to confirm the entered age. The specific scenes for the experiments are discussed in Chapters 5, 7 and 8.

3.6.5 Encountered-Type Haptic Feedback

This system provides encountered-type haptic feedback to the user by using the dominant hand's index fingertip position to control where the rig positions the button control panel. The fingertip's distance to all buttons in a scene is calculated during every cycle of the *VR Test* application and the shortest distance to a button identified, this button position becoming the target for the rig to position itself to align to. A network packet from the headset (Section 3.3.4) containing the fingertip position and button target position is sent to the *QuestG2CoreBridge* application, which calculates where the centre position of the rig carriage must move to in order to align one of the unique button types on the button control panel to the target button position. This position G-code is then sent to the g2core firmware which controls the motors of the rig to move the carriage to the target position, as depicted in Figure 3.11. When the virtual and real buttons are aligned to within an accuracy of 0.1mm or less, the user is then able to click on the virtual button while simultaneously feeling the real physical sensation from the real world button. The control diagram depicting the negative feedback loop to achieve $< 0.1mm$ accuracy is provided in Figure 3.12.

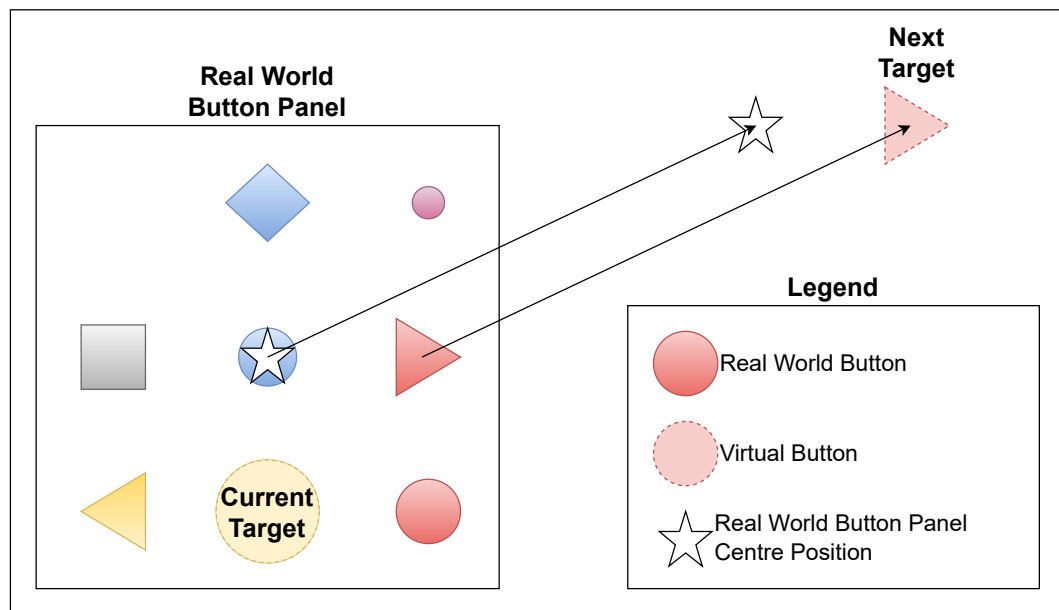


Figure 3.11: A depiction of the ETHD operation.

3.6.6 Safety Height

The *Safety Height*, a transparent plane which hovers above the virtual button control panel in the *VR Test* application, lets the user know visually where the regions are

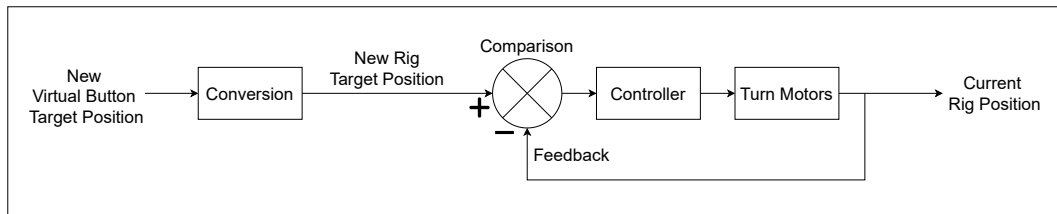
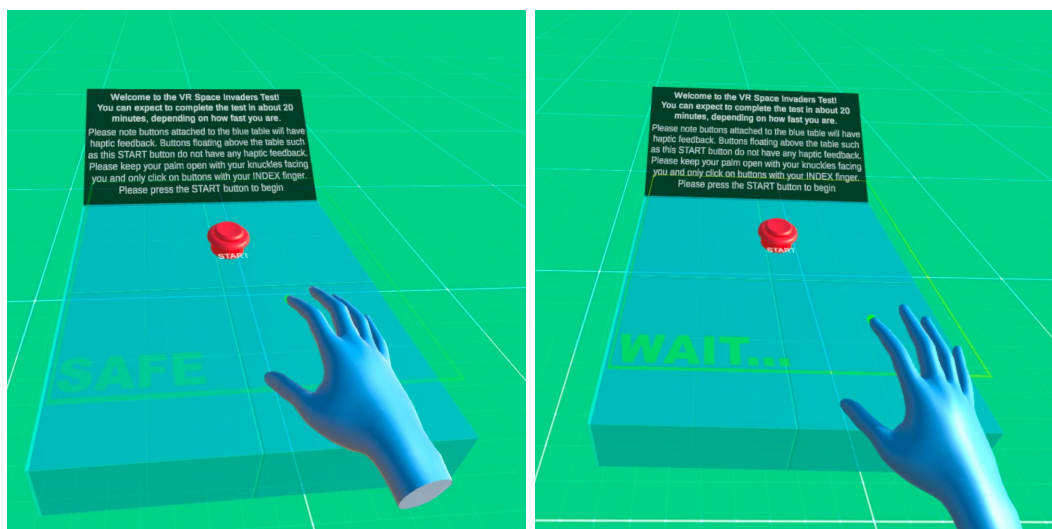
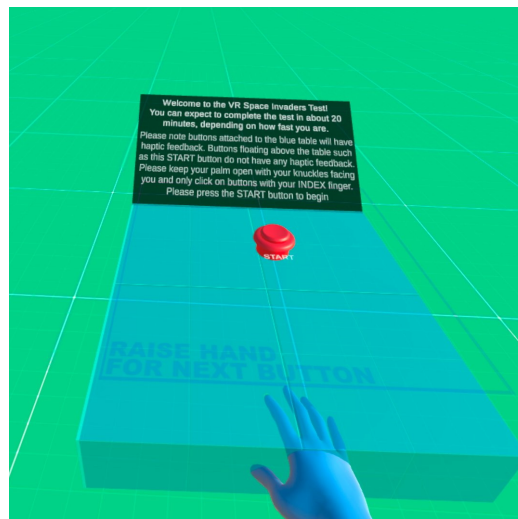


Figure 3.12: Control diagram depicting the negative feedback loop to achieve $< 0.1mm$ positional accuracy.



(a) Safe to click

(b) The user must wait until the rig has stopped



(c) The user must raise their hand above the Safety Height to choose a new button

Figure 3.13: Safety Height of indications for when it is safe to click (a), when the rig is in motion (b) and when the user is prompted to raise their hand (c).

for rig movement to be enabled and disabled. If the user moves their hand over the *Safety Height*, the *VR Test* application searches for a new button target, and if the target has changed, the rig will start the alignment process described in Section 3.6.5. If the user's hand is below the *Safety Height*, the rig will not move at all, and if it was already in motion it will decelerate rapidly to a standstill. The *Safety Height* changes colour and information text to alert the user of when the ETHD rig is in motion, or, if the rig is stationary, that they need to raise their hand above it to safely allow the ETHD to move to a new target button position. When the indicator is green and says "SAFE" (Figure 3.13a) this indicates that the user can click on the closest button, as the ETHD is stationary and the virtual and physical button positions are now aligned. The buttons themselves had a visual cue, as all buttons were under the transparent control panel by default, and only pop up above the control panel when it is safe to click it. When the indicator is yellow and says "WAIT" (Figure 3.13b) this indicates that the rig is in motion and the user must not try to click any button at the time. When the indicator is purple and says "RAISE HAND" (Figure 3.13c) this indicates that the user needs to raise their hand above the *Safety Height* if they want to choose a new button to click.

3.6.7 Control Schemes

Two control schemes can be used for how the system operates to provide haptic feedback, these being the *User Selected Target* and *Application Selected Target* control schemes.

With the *User Selected Target* control scheme, the process described in Section 3.6.5 is performed, whereby the user's proximity to a button determines where the rig moves. With this control scheme, the application monitors the user's proximity to the buttons in a scene to find the nearest one and moves the rig accordingly. The benefits of this scheme are that it is completely dynamic and the system will constantly adjust to the user's will, similar to how any user interface works. The disadvantage is that this process can be slow and the user has to wait for the rig to stop before being able to click on a button.

With the *Application Selected Target* control scheme, the application already has a list of button positions to go through sequentially. After the user clicks a button and raises their hand above the *Safety Height*, the application immediately sends a message for the rig to move to the next position. This scheme is less flexible in that the user has to follow the sequence dictated by the application, but is much faster

Table 3.2: Target, average and max speeds and standard deviation results for 10%, 40%, 70% and 100% ETHD speed profiles

Speed Profile	No. of measurements	Target Speed (m/s)	Average Speed (m/s)	Max Speed (m/s)	Standard Deviation
10%	835	0.125	0.113	0.177	0.0533
40%	610	0.500	0.417	0.707	0.2100
70%	556	0.875	0.451	0.980	0.3060
100%	39001	1.250	0.509	1.640	0.3940

than the *User Selected Target*, and allows the user to feel like the next object was ‘always there’, requiring no waiting time for the user. One caveat of this scheme is that the rig needs to move quickly to the next target and outpace the user or the illusion will be broken. The **Encountered-Type Haptics for the Oculus Quest - Control Schemes** video demonstrates these control schemes.

3.7 System Performance

Speed data from the rig was recorded during the final testing phase and when the actual experiments were conducted. The *QuestG2CoreBridge* application recorded the instantaneous speed captured from the g2core firmware logs for each speed profile during the system runtime. The VR Alien Shooter Game Experiment discussed in Chapter 5 used four different speed profiles of 10%, 40%, 70% and 100%, which consisted mainly of shorter movements, as the buttons for the layout of this experiment were placed closely together so there were less logs for instantaneous velocity from point to point. The number of movements also depend on the user interactions, as this experiment used the *User Selected Target* control scheme. The VR Fitts’s Test Experiment, from Chapters 7 and 8, only used the 100% speed profile and consisted of short to long movements, the latter resulting in more instantaneous velocity data being captured. The nature of this experiment had users moving constantly as it used the *Application Selected Target* control scheme. Due to these factors, Table 3.2 indicates that the number of instantaneous speed measurements for the 100% speed profile far outweighed the other speed profiles.

Table 3.2 summarises the speed data recorded in the g2core logs, and indicates that the average and maximum speeds increased as the target speed for the speed profiles

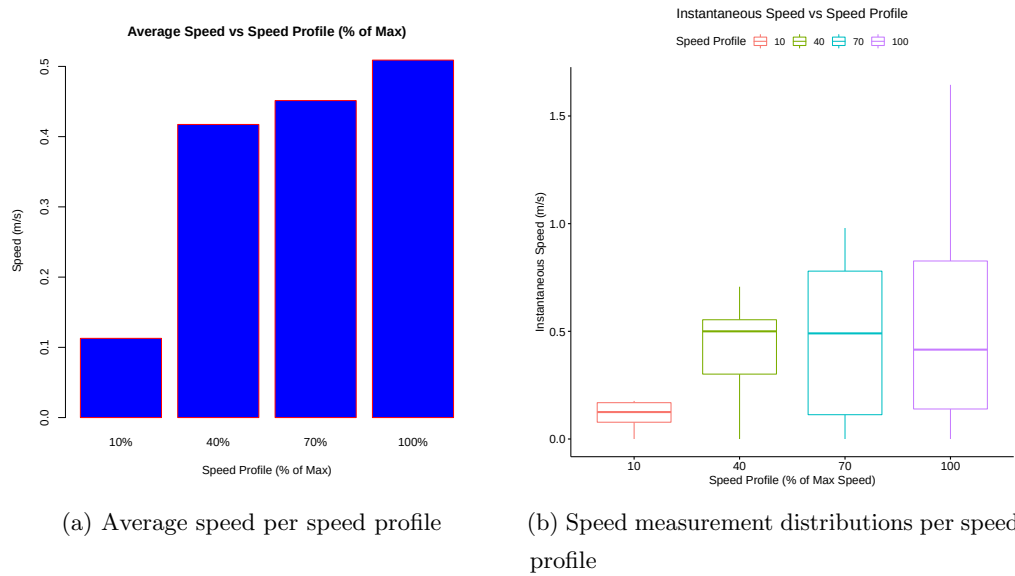


Figure 3.14: Observed speeds for each speed profile.

increased. Figure 3.14 visually summarises these observations, with the average speed not increasing linearly, The 10% profile's average speed being much lower than the other speed profiles, and the averages for the 40%, 70% and 100% speed profiles increasing somewhat linearly, but are not far off from each other. Figure 3.14 also indicates that the maximum instantaneous speeds recorded per speed profile are all above the target speeds, with the 100% profile achieving $1.64m/s$, far above the desired speed of $1m/s$. These kinds of high speeds are probably only occurring over larger distances found in the VR Fitts's Test Experiment where the rig has more time to accelerate. The 10% and 40% profiles have much more predictable speeds than the 70% and 100% profiles which have a larger range. The 70% and 100% profiles have a very similar range of speeds recorded in the inter-quartile range, with the upper whisker of the 100% profile being much larger, indicating the potential to reach higher speeds. Maximum speeds observed above the target speeds are noted, as it appears that when the g2core firmware calculates a trajectory for the rig, it will allow it to move to high instantaneous speeds, even above the limits specified. This speed data from the rig gives an idea of the kind of performance that can be expected for each speed profile, and will assist in understanding some of the results observed for the VR Alien Shooter Game Experiment in Chapter 5 and the VR Fitts's Test Experiment in Chapter 8.

3.8 Conclusions

The *Fast ETHD* system has been designed with performance and safety in mind, with all the design requirements being met and, in particular, that the rig is capable of reaching speeds well above $1m/s$. While the rig is capable of delivering excellent performance, it does have inherent delays in its design, which were reduced to be as minimal as possible. The high performance of the system, along with its latency caveats, will affect how users interact with it, and will be explored in the VR Alien Shooter Game Experiment (Chapter 5) and the VR Fitts's Test Experiment (Chapter 8).

With high performance also comes a high risk to users, and the system has been designed with such features as the *Safety Height*, the emergency stop button and the cardboard button panel to prevent collisions and reduce harm to users in the unlikely even of a collision.

These design decisions can be used by other researchers working in the field of encountered-type haptic feedback to improve their work, and can be extended and improved upon in future work, especially regarding latency. The details regarding these design decisions during development should be noted so that problems are not repeated during future developments, thereby enabling researchers to focus on improving this technology.

3.9 Chapter Summary

This chapter looked at the design requirements of the *Fast ETHD* system, its features and the performance of the speed profiles used for the experiments of this study. The rig needed to be fast and accurate enough to track human hand movements, while keeping the user safe. The VE needed to keep players at ease for maximum immersion and to enable them to focus on their tasks, while interactions with buttons needed to feel responsive and natural, the data from these interactions being captured accurately for analysis. The *Fast ETHD* system incorporated high-speed motors, controllers and linear actuators in its ETHD to track users quickly, while the *VR Test* and *QuestG2CoreBridge* applications ensured accurate positioning and responsive buttons clicks through their coordinate system alignment feature, as well as accurate capturing of movement data. The *VR Test* application was also designed to keep the player relaxed and immersed in a bright VE, as well as focused on their tasks.

Four speed profiles were defined for the experiments: 10%, 40%, 70% and 100%. The 10% speed profile's average speed was noted to be lower than the others, with the average speed for the other profiles increasing non-linearly. The maximum speed for the 100% speed profile was recorded to be $1.64m/s$, which is higher than the initially desired speed of $1m/s$.

The next chapter explores the concepts of immersion, presence and UX and how they can be measured quantitatively.

Chapter 4

Literature Review: Immersion, Presence and User Experience

This chapter provides a literature review on the concepts of immersion, presence and User Experience (UX), these concepts being further described within their constituent components. The questionnaires that were designed specifically to analyse these concepts quantitatively are discussed in addition to reliability metrics.

4.1 Introduction

The previous chapters have reviewed how fast the Encountered-Type Haptic Display (ETHD) for this study needs to be, with being physically fast being inadequate to convey what the device can add to the Virtual Reality (VR) experience of users. The device needs to be evaluated on its contribution to the immersion, presence and UX felt by users, and using this empirical data will contribute to understanding ETHDs and their effects on the VR experience. This data and the measurement methods used will also contribute to advancing the technology by bringing awareness to future ETHD researchers and designers of the potential methods available to evaluate these devices.

The proposed ETHD design that will deliver the haptic feedback needed to be evaluated for its effects on immersion, presence and UX arising from its usage, these concepts being explored in detail, with different survey instruments being used in an attempt to measure these concepts for use in this study.

4.2 Immersion and Presence

The quality of a VR experience can vary widely and is determined by many factors, with the definition and need to quantify the experience of the two concepts of immersion and presence frequently being raised in VR literature.

Immersion can be defined as the extent to which a computer display is able to deliver an *inclusive*, *extensive*, *surrounding* and *vivid* illusion of reality to the senses of a user interacting with a Virtual Environment (VE) [10]. *Inclusive* indicates how well physical reality is hidden, *extensive* refers to how many of the body's senses are accommodated, *surrounding* refers to the expansiveness of the VE and *vivid* is concerned with the quality of displays and how much information can be conveyed to users. These qualities of immersion mainly refer to the display of information to the user, with *matching* being another quality, which requires that there is a close link between the user's proprioceptive feedback (position and movement) and the displays. While the display qualities refer to the quality of the VE graphics and the resolution of the displays, *matching* requires minimal latency between the actions of the user and the system response.

While immersion can be quantifiable by the quality of information it provides to user senses, presence can be defined as the state of consciousness of the user, which is directly affected by their sense of being in the VE [10]. Users who are highly present in a VE should be more engaged in the virtual world than the surrounding physical world, and should consider the displays as places rather than just images that they see. Presence is more centered on how well a user's behaviour in the VE will match their behaviour in similar situations in real life.

Slater *et al.* explored the relationship between immersion, presence and task performance in VR [34]. Users in their study were required to learn a set of moves for the game of Tri-Dimensional Chess in VR, or through a TV screen (the *surrounding* quality of immersion), and replicate the end state of the board on the real chess board. Two environments were also used, a realistic garden scenario and a plain environment with the chess game suspended in a void (the *vividness* quality of immersion). Subjects who were trained in VR were better at replicating the chess board than those trained through the TV screen, with task performance also being better in those who were exposed to the more realistic garden scenario. When interpreted, it would appear that the results showed that greater immersion (with regards to *surrounding* and *vividness* qualities) produced better task performance, supporting the idea that immersion improved comprehension and memorisation of the

3D environment and movement sequence. Slater *et al.* argued that better immersion would improve performance in certain tasks due to the high quantity and quality of information available. They state that a presence brings about more natural reactions to a situation, which may or may not have anything to do with the level of task performance by the user.

Immersion and presence in a VE are regarded as being important to enhance the VR experience, with higher levels being desired, which have positive effects on related outcomes, such as learning and task performance. It is therefore important to be able to measure and quantify these qualities, with two tools that try to formalise this evaluation being questionnaires by Slater *et al.* and the more in-depth Presence Questionnaire (PQ) by Witmer and Singer [32, 35].

Slater *et al.* tried to assess the influence that a variety of factors had on the level of presence experienced by users in immersive VEs [35], their focus being mainly on the psychological aspect. The Slater-Usuh-Steed (SUS) Questionnaire has questions related to users' subjective experiences of presence in the VE along with other questions related to their experience with computers and VR, vocation, susceptibility to vertigo and motion sickness, feelings of nausea and their adaptability to new environments. The presence questions focused on three things: the user's sense of *being there* in the virtual world; the extent to which the virtual world became the 'reality' for them so that they forgot about the real world to a degree, and the feeling the user had that the virtual world they were subjected to was *something they saw* or *somewhere they visited*. Slater *et al.* discuss what would be observed of someone who has a strong sense of presence in VR and noted it was concerned with locality, that they would believe that they were in one particular place rather than another, and react to events happening in that environment. They note that having a virtual body for the user to associate with contributes to having a strong sense of presence, as they would 'believe' that they were in that locality.

The PQ by Witmer and Singer [32] was developed to measure the degree to which users experience the construct of presence in a VE, which depends on a number of factors that collectively are able to shift the attention of the user from the surrounding physical environment to the VE. Presence is a matter of focus, which occurs when the user redirects their attentional resources towards something they find meaningful and interesting. To grab the user's attention, they must have a sense of *involvement* and *immersion*, the former being the psychological state experienced when a person focuses their energy and attention on a coherent set of stimuli or meaningful activities and events. Users become more involved in a VE, which increases their sense of

presence, as they focus more of their attention on the VE stimuli than the surrounding physical environment. Higher levels of involvement and immersion will produce higher levels of presence in a VE.

The components of the PQ are provided in four categories (*control*, *sensory*, *distraction* and *realism*), with users answering the questions on a 7-point Likert scale that ranges from negative to positive sentiments toward an aspect of immersion and presence. Control factors focus on how much control the user has in the VE, acceptable levels of delay between actions and consequences, predictability of the environment and the ability to modify the environment. Sensory factors are focused on the amount of information presented to the user's senses, the detail of the environment, and being able to move through the VE and observe it in a realistic way. Distraction factors focus on isolating the user from the surrounding physical environment, directing their attention to the VE and the comfort of the interface devices. Realism factors focus on how realistically the VE scene is presented to the user, the consistency of the information displayed throughout the VE, the meaningfulness of the experience, and how the user reacts when stopping the simulation to return to the real world.

Instruments such as the PQ need to be valid and reliable in order to be used with confidence. Validity refers to the extent to which an instrument can measure what it is meant to measure, while reliability refers to how consistently the instrument is able to measure the intended concepts. Cronbach's alpha is a measure of the internal consistency of a scale and is commonly used as an index of reliability, being represented as a number from zero to one, with higher values indicating better internal consistency [98]. When constructing and evaluating the PQ, Witmer and Singer found that the internal consistency of the PQ, based on Cronbach's alpha, was 0.81, indicating a high degree of reliability. Witmer and Singer also note, regarding content validity, that the PQ items were derived from factors found in previous studies on presence [32]. They also used cluster analysis to evaluate construct validity, and verified that the PQ is a valid construct, which is apparent in the supporting evidence, such as the consistent positive correlations between presence scores and task performance in VEs. Task performance in an environment is affected by many factors, including the skill level and abilities of the user, and it should therefore not be assumed that presence measured by the PQ would always be a good indicator of better performance. However, in general, it has been shown to be a good indicator of task performance in a VE, with better presence scores being associated with better task performance. Witmer and Singer also conducted factor analysis on the PQ and determined that it was a reliable measure of presence [99].

Many studies have used the PQ and SUS questionnaires to evaluate immersion and presence in VEs. Youngblut and Huie used both questionnaires to evaluate presence in the Virtual Emergency Response Training System (VERTS) prototype system, which was created by the United States Department of Defence to investigate the training effectiveness of VR for nuclear, biological and chemical special-response teams [8]. The results of the study supported the assumption that there is a relationship between presence and task performance, which the questionnaires helped to interpret. Vora *et al.* developed a VR system used for aircraft inspection training, with the Witmer-Singer PQ being used to measure the degree of presence experienced in a virtual cargo bay that users were trained on to find defects [9]. The VR system was also evaluated against a computer-based 2D training program called ASSIST, with the results showing that it could be used as a training tool for visual inspection tasks due to the high scores on immersion and presence, the subjects indicating that they preferred the VR system over the ASSIST program with respect to the effectiveness in improving speed and accuracy of visual searches.

With the concepts of immersion and presence being important to VR, evaluating them is essential in this study to determine how ETHDs contribute to the VR experience. Furthermore, existing tools, such as the SUS Questionnaire and PQ, have already been used in many studies and shown to be reliable measurement methods. The use of one or more of these tools would provide valuable quantitative data to measure these important concepts and for comparisons with previous studies.

4.3 User Experience

Besides the concepts of immersion and presence, it would also be useful to measure the User Experience (UX) in the VE as a whole, the ISO 9241-210 specification defining UX as “a person’s perceptions and responses resulting from the use and/or anticipated use of a product, system or service” [38]. UX can be viewed as a concept that encompasses all types of emotional, cognitive or physical reactions to the actual or assumed usage of a product, and while this definition is general and abstract, it is not sufficient to be able to quantitatively measure the quality aspect of a product [36].

The success of an interactive product depends on it providing a good UX, making it important to be able to quantitatively measure UX in an efficient and reliable manner. A different interpretation of UX more suited to quantitative measurement would be to view it as a set of distinct quality criteria. This would include usability criteria, such as efficiency, controllability or learnability, and non-goal oriented or

hedonic quality criteria, such as aesthetics, stimulation, fun factor and emotions. This definition splits the notion of UX into simple, distinct and well-defined aspects of UX that can be measured independently.

Questionnaires are widely used to assess the usability and quality of software products, with Laugwitz *et al.* having developed the User Experience Questionnaire (UEQ) which aimed to allow end users to quickly assess a product in a comprehensive manner [37]. Their goal was to give users a simple and immediate way to express the feelings, impressions and attitudes experienced while interacting with the product. The UEQ has two classes of items, one for measuring perceived attractiveness of the product and the other for measuring the quality of the product on relevant aspects. These item classes are then divided into six scales of Attractiveness, Perspicuity, Dependability, Efficiency, Novelty and Stimulation, with users rating the attributes of these scales on a 7-point Likert scale ranging from negative to positive sentiment. The scales have the following focus:

- Attractiveness - the overall impression of the product,
- Perspicuity - how easy it is to become familiar with the product,
- Efficiency - users solving tasks with unnecessary effort,
- Dependability - the level of control the user feels during the interaction,
- Stimulation - how exciting and motivating the product is to use and
- Novelty - how creative and innovative the product is.

The UEQ has been evaluated for its level of reliability and construct validity, with high values for Cronbach's alpha being determined to lie between 0.65 and 0.89 for the scales, indicating high reliability [37]. Another study showed that scores from the UEQ correlated highly with the scores from the AttrkDiff2 questionnaire which had similar scales. This correlation, as well as a factor analysis that was carried out, were indicators of good construct validity of the UEQ, with a number of studies determining that it had high reliability and construct validity [36,100]. The UEQ has been proven to be a reliable and valid quantitative measure for UX that is easy to apply, and can be used to complement data from other evaluation methods [36].

Chertoff *et al.* developed the Virtual Experience Test (VET) which was designed to measure the holistic experiences of users interacting with VEs [47]. The VET questionnaire is based on Experiential Design, which is a process used to create an

experience based on five elements – sensory, cognitive, affective, active(personal) and relational(social). The five elements entail:

- Sensory - the stimuli presented to the user and their perception of it.
- Cognitive - the engagement a user has with an experience.
- Affective - the emotional state of the user within the experience.
- Active - to how connected the user feels towards the experience.
- Relational - the social aspects of the experience if it is multi-user.

Incorporating Experiential Design to provide a more holistic experience with these five elements enables the potential for improvements in task performance and sense of presence within a VE. The scores from the VET were confirmed to correctly predict increases in presence, as measured by the ITC-Sense of Presence Inventory questionnaire and can thus be used to evaluate the holistic experiences of users in VEs [101].

Measuring UX appears to be valuable in determining how much of an impact a product will have on its intended users. Using one or more established tools to measure UX, specifically the UEQ and VET, was considered useful in this study to determine the overall feelings of users towards the VR experience presented to them. The measured data could also be used to reaffirm other measurements, such as that of immersion and presence, and for comparison to previous studies.

4.4 Chapter Summary

This chapter presented a literature review on the concepts of immersion, presence and UX. These concepts are important in designing a virtual experience, as these can mean the difference of the user having the feeling of actually being part of the VE or not. Being able to measure these concepts thus becomes important, with the PQ, SUS Questionnaire, UEQ and VET tools being discussed, along with the reliability metrics for each one in terms of Cronbach's alpha.

The next chapter discusses the VR Alien Shooter Game Experiment that was designed to answer RQ1, “*What effects on immersion, presence and UX are observed in users as ETHD speed increases?*” These concepts were measured, using the PQ and UEQ, for different speed profiles of the *Fast ETHD* system to answer RQ1.

Chapter 5

VR Alien Shooter Game Experiment

This chapter discusses the methodology and results of the VR Alien Shooter Game Experiment that was conducted to answer RQ1. Discussions and analysis on experiment methodology, equipment, software, user interfaces, data capturing, data transformations, sample size estimations, participant selection and experiment procedures are provided. The concepts of immersion, presence and User Experience (UX) discussed in Chapter 4 are broken down into constituent components in the Presence Questionnaire (PQ) and User Experience Questionnaire (UEQ) to enable their quantification. Analysis was done for each of these components and game performance data as the Encountered-Type Haptic Display (ETHD) speed was varied, to determine if users were able to perceive an improvement in immersion, presence and UX as ETHD speed increased. Analyses was also done on UX components to determine overall user sentiment on the system and the experience.

5.1 Introduction

This chapter discusses an experiment that investigated how ETHD speed affects the user's experience of immersion, presence and UX. The results on the perceived changes of these aspects as the speed increases will be used to answer RQ1, "*What effects on immersion, presence and UX are observed in users as ETHD speed increases?*" This experiment is referred to as the **VR Alien Shooter Game Experiment**, which was designed to utilise the hand tracking capabilities of the Oculus Quest and the *Fast ETHD* system.

It required players to take control of a spaceship using a control panel interface with

buttons to shoot down incoming aliens and avoid taking damage from their bullets, this being reminiscent of the gameplay from the classic arcade shooter game *Space Invaders* [42]. The player starts off with a single shot weapon, with skilled players unlocking the *Double Shot*, *Big Shot* and *Laser Shot* upgrades to assist in taking down more aliens at a faster rate. The game was played on the Oculus Quest, with players receiving haptic feedback from the *Fast ETHD* system. Users were required to enter their sentiments on the experience through modified versions of the PQ and the UEQ, on a subset of questions from the component scales of these questionnaires that were suspected to be affected by the speed of the ETHD. Users played the game on four different speed profiles of the ETHD, which had varying effects on the experience, and were asked to answer these questions after each game round ended. A total of 25 participants took part in this experiment, which was above the minimum requirement of 21 participants. The data from the questions across all users and speed profiles were then analysed to determine the extent to which users perceived these speed differences.

5.2 Experimental Design

The aim of this experiment is to determine if users are able to perceive increases in immersion, presence and UX as ETHD speed increases. As discussed in Chapter 4, the PQ is renowned for measuring immersion and presence (see Appendix B for the original questionnaire) and the UEQ is an excellent tool for measuring UX (see Appendix C for the original questionnaire). These were chosen to collect information about these concepts as they were rated for high reliability based on Cronbach's alpha and were the most widely used questionnaires for these concepts when compared to similar tools. The experiment design decisions were made by considering the number of speed profiles, and the number of questions for the PQ and UEQ, that users would be exposed to, with measures put in place to reduce the effects of confounding variables. Sample size estimations were done before the experiment began, to determine the minimum number of participants needed to produce accurate results, while factoring in how much resources in terms of time would be required.

5.2.1 Modifications to the Presence and User Experience Questionnaires

The total number of questions across both questionnaires would have been excessive for users to answer, especially if they were required to complete it multiple times, due to their being required to answer them after every ETHD speed profile had been experienced. Some of the scales of the PQ were also deemed not to be applicable to this experiment due to its own variations and limitations, and were thus omitted, in a similar fashion to the work done by Kreimeier *et al.* [102].

As both questionnaires had related questions or attributes grouped into scales for combined scores on particular aspects, the scales that were expected to be affected by ETHD speed were chosen for *speed variation analysis*, two from the PQ and three from the UEQ. The other five scales of the PQ were not applicable and excluded. As the UEQ is applicable to many aspects of product evaluation, the questions from the remaining three scales were answered just once by users at the end of the test for *overall sentiment analysis*.

The PQ scales of *Possibility to act* and *Quality of interface* were determined to be affected by ETHD speed, with some of the questions being directly related to how the user perceived the responsiveness of the *Fast ETHD* system and thus considered for *speed variation analysis* (Table 5.1).

Table 5.1: The modified Presence Questionnaire (PQ version 3.0) used in the VR Alien Shooter Game Experiment.

Question	Scale	Analysis Type
How much were you able to control events?	Possibility to act	Speed Variation
How responsive was the environment to actions that you initiated (or performed)?	Possibility to act	Speed Variation
Were you able to anticipate what would happen next in response to the actions that you performed?	Possibility to act	Overall Sentiment
How completely were you able to actively survey or search the environment using vision?	Possibility to act	Overall Sentiment
How much delay did you experience between your actions and expected outcomes?	Quality of interface	Speed Variation

Table 5.1 – continued from previous page

Question	Scale	Analysis Type
How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?	Quality of interface	Overall Sentiment
How much did the control devices interfere with the performance of assigned tasks or with other activities?	Quality of interface	Speed Variation

For the UEQ, all the questions were used but only the scales of *Attractiveness*, *Dependability* and *Efficiency* were chosen for *speed variation analysis*, as some of the attributes in these scales were directly related to how the the user perceived the responsiveness and user-friendliness of the *Fast ETHD* system, with questions for *Novelty*, *Perspicuity* and *Stimulation* being exclusively for *overall sentiment analysis*. Table 5.2 provides the left and right attributes for these scales, which represent sentiment ranging from mostly negative to mostly positive, or *vice versa*.

Table 5.2: The modified User Experience Questionnaire used in the VR Alien Shooter Game Experiment.

Left Attribute	Right Attribute	Scale	Analysis Type
annoying	enjoyable	Attractiveness	Speed Variation
good	bad	Attractiveness	Speed Variation
unlikable	pleasing	Attractiveness	Speed Variation
unpleasant	pleasant	Attractiveness	Speed Variation
attractive	unattractive	Attractiveness	Overall Sentiment
friendly	unfriendly	Attractiveness	Speed Variation
unpredictable	predictable	Dependability	Overall Sentiment

Table 5.2 – continued from previous page

Left Attribute	Right Attribute	Scale	Analysis Type
obstructive	supportive	Dependability	Speed Variation
secure	not secure	Dependability	Overall Sentiment
meets expectations	does not meet expectations	Dependability	Speed Variation
fast	slow	Efficiency	Speed Variation
inefficient	efficient	Efficiency	Speed Variation
impractical	practical	Efficiency	Speed Variation
organised	cluttered	Efficiency	Overall Sentiment
not understandable	understandable	Perspiciuity	Overall Sentiment
easy to learn	difficult to learn	Perspiciuity	Overall Sentiment
complicated	easy	Perspiciuity	Overall Sentiment
clear	confusing	Perspiciuity	Overall Sentiment
creative	dull	Novelty	Overall Sentiment
usual	leading edge	Novelty	Overall Sentiment
inventive	conventional	Novelty	Overall Sentiment
conservative	innovative	Novelty	Overall Sentiment
valuable	inferior	Stimulation	Overall Sentiment
boring	exciting	Stimulation	Overall Sentiment

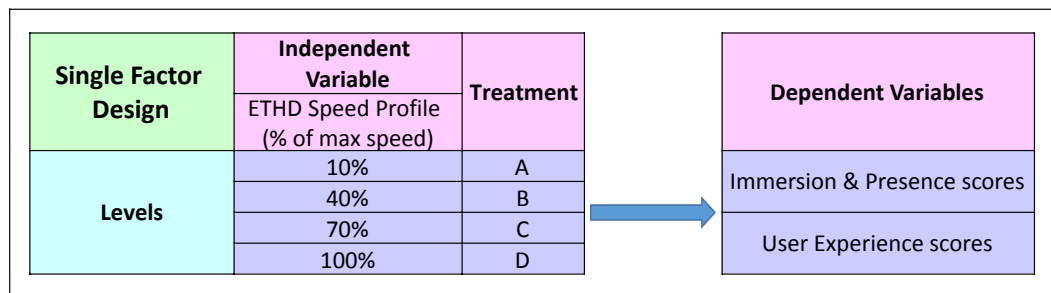
Table 5.2 – continued from previous page

Left Attribute	Right Attribute	Scale	Analysis Type
not interesting	interesting	Stimulation	Overall Sentiment
motivating	demotivating	Stimulation	Overall Sentiment

5.2.2 Measurement Considerations

The VR Alien Shooter Game Experiment used a 1×4 within-subjects design, the ETHD speed profile being an independent variable in this experiment, with four equally spaced speed profiles being considered as treatments, these being 10%, 40%, 70% and 100% of the maximum speed. The dependent variables of immersion, presence and UX scores were acquired for each of these speed profiles, with Table 5.3 summarising the independent variables, treatments and dependent variables.

Table 5.3: The design for levels of ETHD speed profile (% of max) resulting in the dependent variables for Immersion, Presence and User Experience scores.



A Randomised Complete Block Design was used for this experiment to reduce the effects of confounding variables, and an example of this across three users is shown in Table 5.4 using the treatment keys from Table 5.3. Due to time constraints, a participant would only go through one block of the four speed profiles. The order of the speed profile treatments from Table 5.3 were randomised for each participant to see if the user ratings were consistent for a particular profile and not affected by a linearly increasing order. A single trial for this experiment consisted of the participant playing the alien shooting game with the ETHD set at a particular speed profile for 45 seconds, followed by their answering the *speed variation* questions from Tables 5.1 and 5.2. In addition to the questionnaire answers, data on the number

of aliens shot, whether the user unlocked the *Double Shot*, *Big Shot* and *Laser Shot* upgrades, number of alien bullets hit and spaceship damage were also collected. After all trials across the speed profiles were completed, the participant was required to answer one last set of *overall sentiment* questions from Tables 5.1 and 5.2.

Table 5.4: The Randomised Complete Block Design for treatments of ETHD Speed over all trials. This table shows an example of the randomised order across three different users.

Randomised Complete Block Design (Single Block Per User)		User		
		1	2	3
Trial	1	C	D	C
	2	B	A	B
	3	A	C	D
	4	D	B	A

5.2.3 Sample Size Estimation

The input speed profile data and the averaged Likert scale user response data are ordinal, their analysis consisting of reporting on the changes in means for each speed profile. If differences in means are found between these speed profiles, the coefficients of their regression model determine if there was an increase or decrease in sentiment observed.

The Kruskal-Wallis test is ideal for ordinal data and was used to test for significant differences between the means. Guidance was taken from the University of North Dakota's *Sample Size Calculation with R* document by Dr. Mark Williamson, which summarised the use of various power analysis techniques in R [103]. According to the document, the sample size for the Kruskal-Wallis test can be determined by doing a sample size estimation on the corresponding ANOVA test plus an additional 15% to get the number of samples per group. The effect size for a One-Way ANOVA, Cohen's f , is suggested to be 0.1 for a small effect, 0.25 for a medium effect and 0.4 for a large effect [104]. Pilot studies suggested that this test would take 20-30 minutes for each participant to complete. A small effect size required 274 participants and a medium effect required 45 participants, both entailing extensive resources in terms of time and test subjects. Due to time constraints, a large effect size of 0.4 was chosen for the value of f (Equation 5.1) with a power of 0.8. The sample size per group

determined was 18.04262 (Figure 5.1) with an additional 15% bringing this number to 20.74901, rounded up to give a target of 21 participants per group.

$$f = \sqrt{\frac{\sum_{i=1}^k p_i (\mu_i - \mu)^2}{\sigma^2}} \quad (5.1)$$

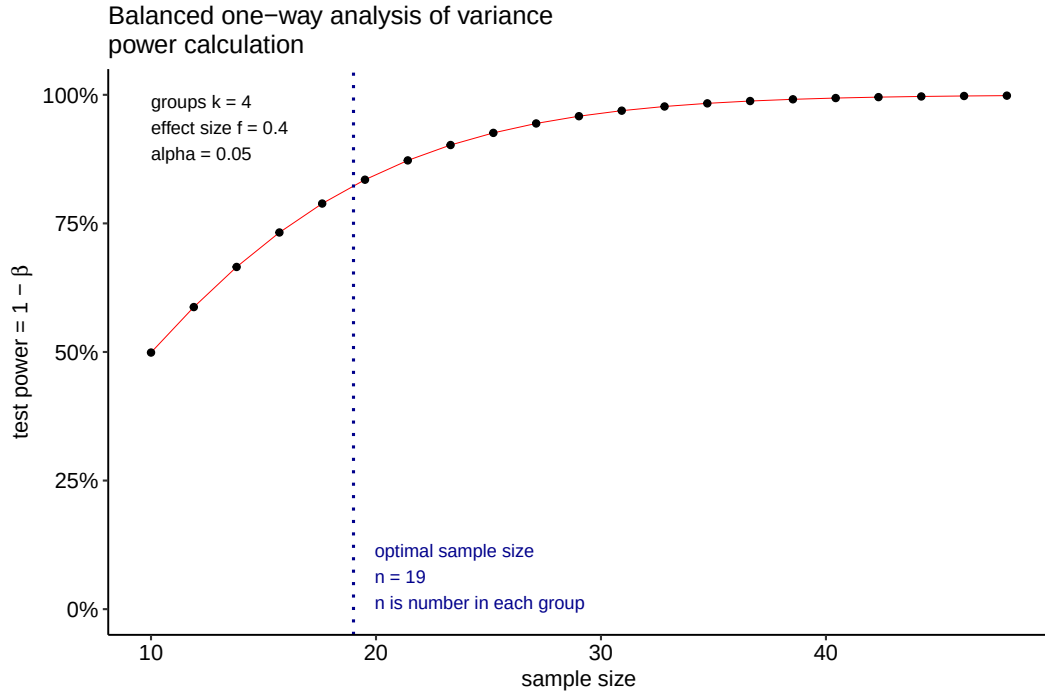


Figure 5.1: Sample Size Estimation for One-Way ANOVA between all four ETHD speed profiles

Ordinal logistic regression is a method used to model relationships between ordinal data and was used to get the regression model, as the input and output data is ordinal in nature. The Relative Standard Error (RSE) is the metric used to evaluate if there are enough values for the regression results to be stable. Ideally this metric should be as low as possible and at least lie between 20%-25% to give stable and confident results [105]. Using this metric, 16 participants results in a 25% RSE, and 25 participants results in a 20% RSE (Figure 5.2). Therefore, the sample size estimation of the Kruskal-Wallis test for a minimum of 21 participants fits in with the RSE calculations, which was the minimum sample size to target for this experiment.

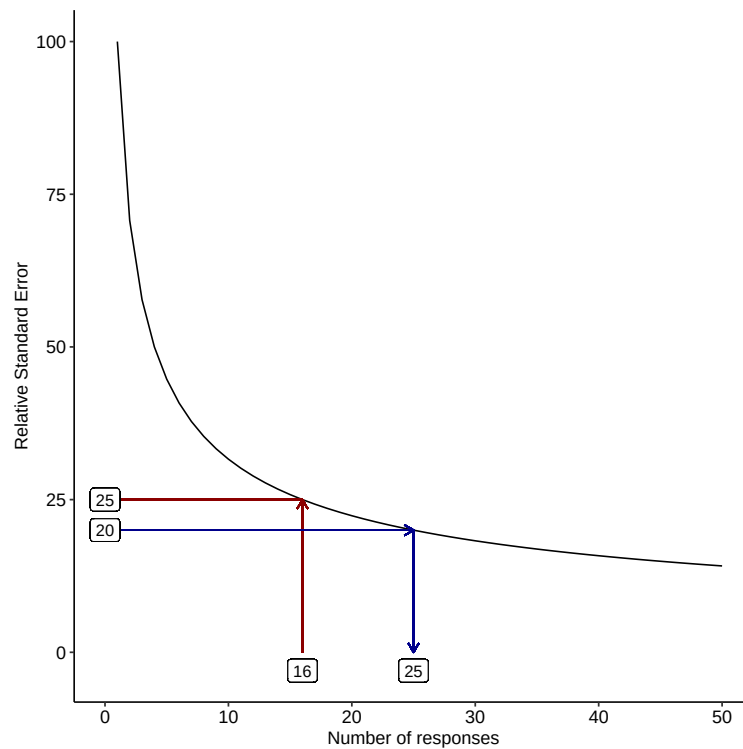


Figure 5.2: Sample Size Estimation for Relative Standard Error

5.3 Experimental Procedure

The VR Alien Shooter Game Experiment entailed users viewing the game on the *VR Test* application, while receiving haptic feedback from the *Fast ETHD* system, the setup and configurations of these being discussed for the experiment. The participant requirements are discussed, as well as the demographics of interest for the volunteers. The experiment setup is then discussed, with details on the training that was provided to participants to become familiar with the haptic feedback system and game mechanics. Participants then played the game with all speed profiles of the ETHD, rating the system for each, with the PQ, UEQ and game performance data being recorded for analysis.

5.3.1 Equipment

The *Fast ETHD* system was used in the VR Alien Shooter Game Experiment to provide realistic haptic feedback to the user with a small amount of delay. The User Selected Target Control Scheme was used (see Section 3.6.7) so that the ETHD moved to the target closest to the user's dominant hand index fingertip position as

soon as it was safe for the user to do so. Users interacted with buttons on a virtual control panel, to which the physical buttons on the ETHD corresponded. When a user touched a new button target, what they saw in VR is what they felt in real life due to the virtual button models matching the shape of the physical buttons very closely, and to the alignment of the virtual and physical button positions. The rig speed was varied between four speed profiles of 10%, 40%, 70% and 100% of the maximum speed to enable them to move between targets in the least amount of time possible. For more details on the *Fast ETHD* system see Chapter 3.

5.3.2 User Interface

The *VR Test* application for the Oculus Quest was used for the subject to interact with the virtual interface, the environment being a bright sunny day with a blue sky and a green ground to make the player feel comfortable and thereby maximise the immersion and presence experienced.

The interface moves through ‘scenes’ for calibration of the virtual and physical height and rotational positions, inputs for dominant hand, gender and age choices, training tasks and the VR Alien Shooter Game Experiment. The player has a view of the spaceship that they can pilot with the control panel and the aliens that they need to shoot down during the experiment scene (Figure 5.3). For more details on the *VR Test* application, see Section 3.3.6.

5.3.3 Participants

An open invitation for participation was made to all students and staff at the School of Electrical and Information Engineering at the University of the Witwatersrand. Emails were sent to the staff and student mailing list by the School’s administration once permission had been obtained, and posters were put up around the building to attract volunteers.

Participants aged from 18 years and older were welcomed to take part in the experiment, and had to be in good health and physically able to play the game. Being a part of the school ensured that they were also familiar with using computers which was required for decent levels of hand-eye coordination needed for the experiments.

A total of 25 volunteers participated in the study which was above the minimum sample size of 21, as determined in Section 5.2.3. Four of the subjects were female,

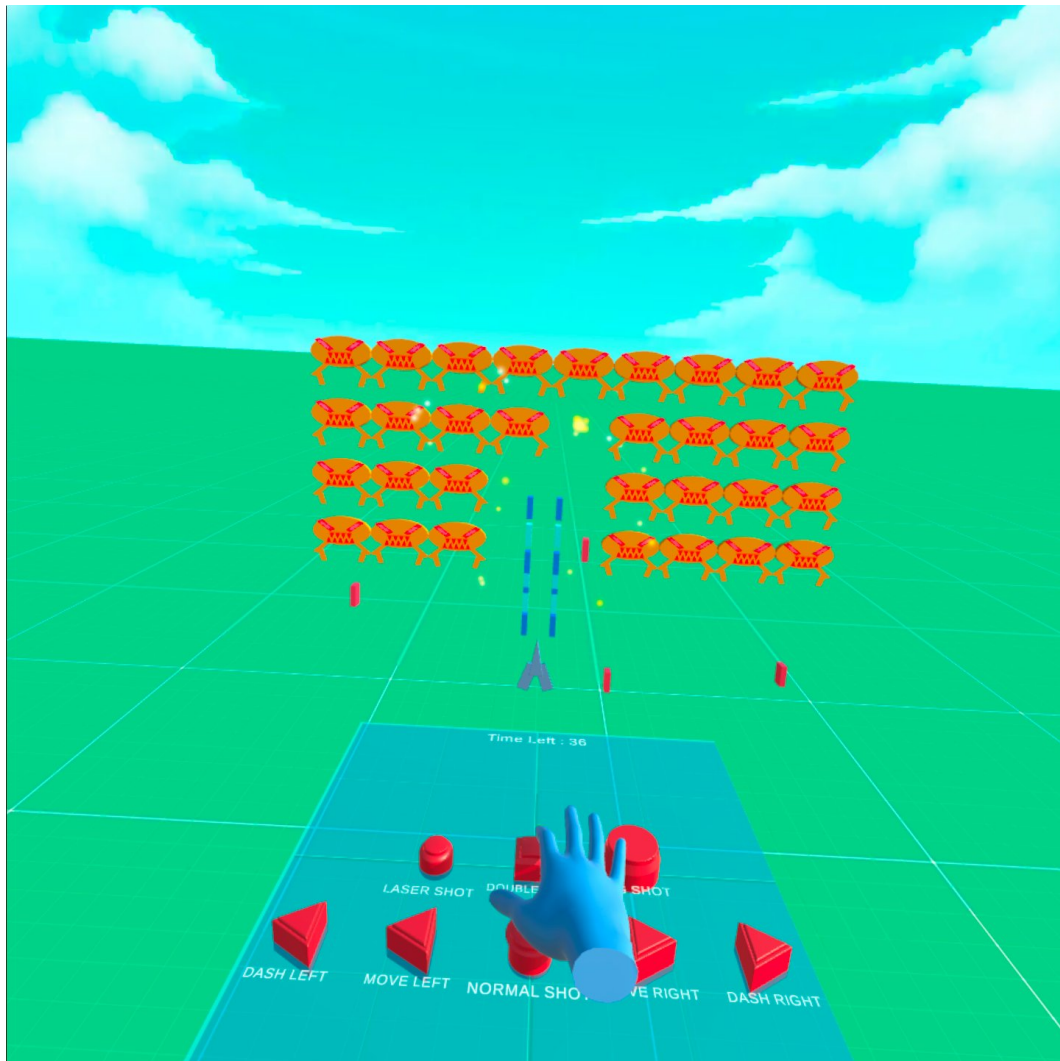


Figure 5.3: The VR interface for the alien shooting game.

all were right-handed, and the average age was 23.8, with their ages ranging from 18 to 64. All participants were able-bodied and had no impairments that would have affected their test results, some subjects wore spectacles, and all had little to no experience with VR, designating them as novice subjects. As there was only one experiment station, appointments were made with each person in terms of when they would be available to play the game.

5.3.4 Test Setup

The experiment was conducted at a dedicated room in the Chamber of Mines building at the University of the Witwatersrand. An LED spotlight was shone onto the wall opposite to the ETHD that the user would be interacting with, to enhance the

ambient lighting in the room and optimise hand tracking. The volunteers were verbally briefed on the procedures and aims of the experiment, asked to read a Participant Information Sheet with more details (see Appendix D), and complete a consent form to proceed with the experiment. All participants had their arm temperature checked with an infrared thermometer to make sure they did not have a fever, as this was conducted during the time of the Covid-19 pandemic, and had to declare that they were not displaying any symptoms at the time.

The *VR Test* application was launched and the Oculus Quest controllers were then manually used in the first calibration scene to align the virtual blue control panel height, centre and rotational positions to the physical ETHD height, centre and rotational positions as laid out Section 3.6.2. The responsiveness of the button clicks were then manually evaluated using the haptic feedback of the ETHD in a test scene. If the buttons were not responsive enough, the height of the virtual control panel was adjusted by 5mm at a time upwards or downwards until the button clicks felt responsive. The headset was then passed onto the subject and assisted with fitting it on comfortably, after which they were requested to read all instructions. After entering their age, gender and dominant hand data, the participants were given training on the system.

5.3.5 Haptic Feedback System Training Phase

The participants were given two training tasks, the first being to familiarise themselves on how the haptic feedback system works. This included how to choose a target, identifying indicators for when the target is safe to click on and clicking on targets correctly. Due to the nature of the hand tracking abilities and limitations of the Oculus Quest, users were encouraged to click buttons with a decent amount of speed and force, as this produced the best results with regards to the system registering button clicks. The 100% speed profile was active throughout this training task.

Participants were first guided to buttons they needed to click on in a predefined sequence and were made aware of the *Safety Height* indicator that notified them if the ETHD was moving or if they needed to raise their hand above it to safely move to a new target button (refer to Section 3.6.6 for more details on the *Safety Height* indicator). The user was guided to click 10 buttons in a sequence to become familiar with the ETHD operation, and upon completion, were allowed to click on any button in any sequence. They could then click on a floating virtual arcade button when they were satisfied with their interaction with the haptic feedback system and its

safety features to move on to the next training task.

5.3.6 Game Practise Phase

The second training task's goal was to familiarise the user with the game itself, this being a practise round without any time limit that preceded the trials for the alien shooting game. This was done to allow participants to become familiar with the game mechanics and improve their score to a level that they were happy with so that the only variable that would affect their rating at the end of a trial would be the ETHD speed. This was also necessary to allow users to get used to the system, as some participants had never been exposed to VR before, let alone haptic feedback in VR or ETHDs.

The 100% speed profile was also active throughout this training task. Users were briefed on the control panel buttons used to pilot the spaceship, with four buttons being used to move and rapidly dash the spaceship left and right, a dedicated button being used to shoot bullets from the spaceship. The armada of 36 aliens would move left to right and then left again, and would drop down slightly when they reached the extreme left or right boundaries, inching closer and closer to the spaceship. If the closest alien dropped to the same height position as the spaceship, the game would end in failure and start again, with no time limitations for these game rounds in the training task.

The aliens would also fire bullets at the user's spaceship, and if an alien bullet hit, it would flash red at that instant to indicate damage taken. However, taking damage does not result in the game ending, with the spaceship being able to take on any amount of damage. Users were instructed to shoot as many aliens as they could before they reached the spaceship, with the aim being to destroy all 36 aliens. Users were also instructed to dodge or shoot the alien bullets to avoid taking damage.

Information was also presented on how to maximise the spaceship's firepower to take down the armada in the fastest time possible. Skilled players were awarded the use of the *Double Shot* button after shooting 10 aliens, which doubled the spaceship bullets that were shot and persisted for the rest of the game. After shooting 20 of the 36 aliens, the *Big Shot* and *Laser Shot* buttons were activated as a choice for a single large once-off shot that destroyed many aliens quickly.

This training task looped indefinitely for users to get used to the game, which would restart if the user wiped out the entire armada or if failure occurred due to the aliens

reaching the spaceship. Users were instructed to click on a floating virtual button to end the training task once they were satisfied with their performance within the game.

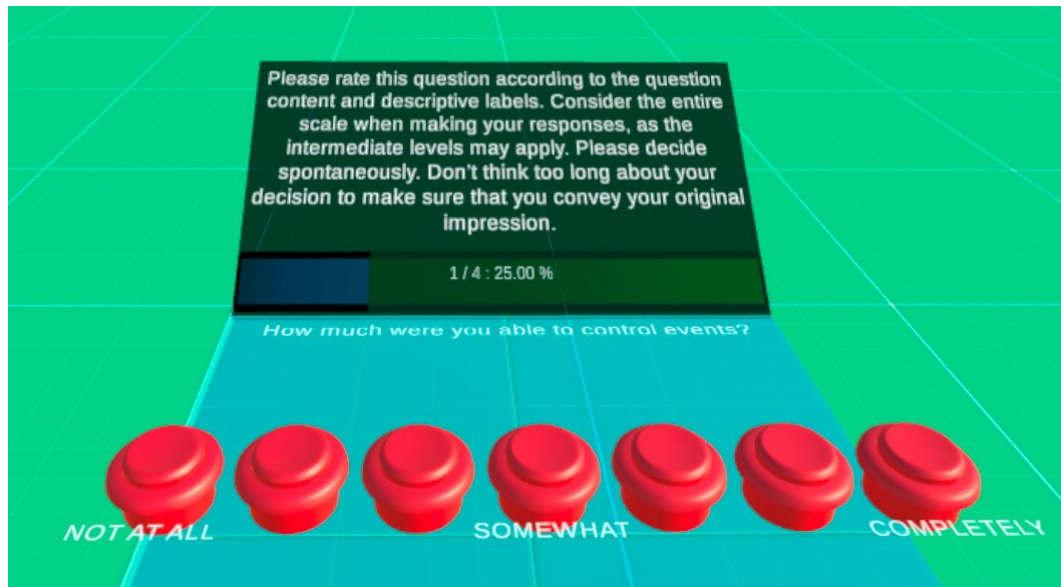


Figure 5.4: An example of the VR representation of a Presence Questionnaire item.

5.3.7 Playing the Game

After a break, the participant played the VR Alien Shooter Game Experiment sequence from which results would be obtained. Each participant played through four rounds of the game, going through all speed profiles of 10%, 40%, 70% and 100% in a random order. Users were now only given 45 seconds to finish each round and attempted to hit as many alien targets as possible in the allotted time limit. When the round had ended from either time running out, the aliens reaching the ship or a successful round of destroying all aliens, users had to then rate their experience with the *speed variation* questions from Tables 5.1 and 5.2 in-game. After playing the four rounds and answering the same set of questions after each round, the users had to answer one final list of *overall sentiment* questions from Tables 5.1 and 5.2 before finishing the experiment. All potential answers to the questions were presented as seven virtual arcade buttons labelled with the original text from the scales seen in Appendices B and C, with Figures 5.4 and 5.5 showing examples of these questionnaire items as presented to users.



Figure 5.5: An example of the VR representation of a User Experience Questionnaire item.

5.3.8 Data Capturing

This section details the types of data captured as well as the manner of their collection, and consisted of the user details as well as the test results. In terms of the user's details, the *VR Test* application captures dominant hand, gender and age data that is entered by the user into memory at the start of their interaction, as well as the time to complete the experiment. Regarding the test results, all questions were rated on a Likert scale ranging from one to seven, which corresponded to the seven buttons presented to the users to answer with. Scores on the total number of aliens hit, whether the user unlocked the *Double Shot*, *Big Shot* and *Laser Shot* upgrades, number of alien bullets hit and spaceship damage taken were also stored in memory. This data is saved to an XML file on the Quest's on-board storage upon completion of the test, with the practise round data being excluded from this file. The *QuestG2CoreBridge* application captured data for the speed profile and the instantaneous speed that the rig moved at from the g2core logs.

5.4 Data Analysis

The PQ, UEQ and game performance data recorded was transformed and prepared for statistical analysis. The Speed Variation Analysis for the two questionnaires and game performance were done, each consisting of scales or categories, the scores of

which were analysed against the four speed profiles of the ETHD to determine how each affected them. This was followed by Overall Sentiment Analysis for three scales of the UEQ to determine how users perceived the system and the experience overall.

The average time spent to complete the experiment was 22.3 minutes, the fastest being 12 minutes and the slowest 33 minutes. Initial setup time, including explanations, signing of consent forms, calibration of the virtual and physical orientations and fitting of the Oculus Quest typically took an additional 5-10 minutes, with approximately 20-25 minutes being needed per subject for the full experiment procedure.

5.4.1 Data Transformations

The following calculations were used to determine the final average score for each scale per ETHD speed profile. All questions from the PQ and UEQ were designed to be answered on a seven point Likert scale ranging in ordinal values from 1 to 7 (Tables 5.1 and 5.2). These ratings were normalised to lie within the range of -3 to $+3$ (Equation 5.2). This correlates to -3 representing the most negative sentiment, 0 representing neutral and $+3$ representing the most positive. When the question attributes were reversed in sentiment (positive to negative), as was done for *Quality of interface* in the PQ and some of the questions in the UEQ, the values were reversed back to negative to positive sentiment before being normalised. The user average for a scale on a particular speed profile was then calculated (Equation 5.3). These user averages will lie between the range of -3 to $+3$, with the number of possible ordinal outcomes being determined by Equation 5.4, and the interval between outcomes determined by Equation 5.5. If *speed variation analysis* was done on a scale, the *overall sentiment* question scores remain constant for all speed profiles, while the *speed variation* question scores would vary per speed profile. The result would be an average score calculated for each speed profile, with the final result calculated being the global average across all users for a scale at a particular speed profile (Equation 5.6). This would then be used for comparison against the other speed profile averages for *speed variation analysis*. For *overall sentiment analysis*, only one global average was calculated.

$$\text{Rating}_{\text{normalised}} = \text{Rating}_{\text{original}} - 4 \quad (5.2)$$

$$\text{PerUserScaleAverage} = \frac{1}{\text{NoOfQuestions}} \sum_{i=1}^{\text{NoOfQuestions}} \text{Rating}_i \quad (5.3)$$

$$\text{NoOfPossibleOutcomes} = (7 \times \text{NoOfQuestions})(\text{NoOfQuestions} - 1) \quad (5.4)$$

$$\text{IntervalBetweenOutcomes} = \frac{1}{\text{NoOfQuestions}} \quad (5.5)$$

$$\text{GlobalScaleAverage} = \frac{1}{\text{NoOfUsers}} \sum_{i=1}^{\text{NoOfUsers}} \text{PerUserScaleAverage}_i \quad (5.6)$$

5.4.2 Speed Variation Analysis

The results obtained per speed profile are presented for the PQ (immersion and presence) scales of *Possibility To Act* and *Quality Of Interface*, the UEQ (UX) scales of *Attractiveness*, *Efficiency* and *Dependability*, and the user game performance data for the *Total Aliens Hit*, *Aliens Hit By Normal And Double Shots*, *Aliens Hit By Laser And Big Shots*, *Alien Bullets Hit* and *Spaceship Damage* categories. Detailed analysis for each of these can be found in Appendix E, with Table 5.5 summarising the results for the speed variation analyses, where the ETHD speed was varied randomly.

The analysis process first looked at the score value frequencies, mean scores and standard deviations per scale, with Equation 5.4 determining the number of possible score outcomes and Equation 5.5 the interval between outcomes. The non-parametric Kruskal-Wallis rank sum test was used to check if there was at least one significant difference in the means. The effect size η^2 , based on the H-statistic obtained from the Kruskal-Wallis test results, was then given, with 0.01–0.06 representing a small effect, 0.06–0.14 being moderate and greater than 0.14 representing a large effect [106]. Dunn's test was then performed to determine which pairs were significantly different. Finally, an ordinal logistic regression (OLR) was performed, the coefficients for the 40%, 70% and 100% speed profiles being inspected in relation to the 10% speed profile for positive or negative effects on user sentiment. The probabilities for each score value arising from this regression model was also inspected for each speed profile.

For all speed variation analyses, there were no statistically significant differences detected in the data distributions across all speed profiles, and all effect sizes were small, which indicates that users were not very sensitive to the range of speeds that they were exposed to. The largest differences were usually found when moving from

Table 5.5: Summary of Speed Variation Analysis Results

Category/Scale	Type	Comments	Speed profile mean score				OLR Coefficients		
			10%	40%	70%	100%	40%	70%	100%
Possibility To Act	PQ	Small increase in immersion and presence scores as ETHD speed increases	1.44	1.53	1.49	1.52	0.24734	0.09878	0.12175
Quality Of Interface	PQ	Small increase in immersion and presence scores as ETHD speed increases	0.827	0.827	0.920	0.960	-0.00621	0.25914	0.18161
Attractiveness	UEQ	Not much effect on UX scores as ETHD speed increases	1.90	1.98	1.92	1.91	0.09177	-0.01998	-0.04654
Efficiency	UEQ	Small increase in UX scores as ETHD speed increases	1.68	1.75	1.72	1.57	0.2296	0.1590	-0.2395
Dependability	UEQ	Small decrease in UX scores as ETHD speed increases	1.55	1.41	1.51	1.51	-0.19617	0.01454	-0.05552
Total Aliens Hit	Game Performance	Small increase in user scores as ETHD speed increases	19.1	20.7	20.4	21.3	0.4928	0.3715	0.4813
Aliens Hit by Normal and Double Shots	Game Performance	Small increase in user scores as ETHD speed increases	18.0	18.5	19.3	19.0	0.3145	0.4471	0.3258

Table 5.5 – continued from previous page

Category/Scale	Type	Comments	Speed profile mean score				OLR Coefficients		
			10%	40%	70%	100%	40%	70%	100%
Aliens Hit by Laser and Big Shots	Game Performance	Small increase in user scores as ETHD speed increases	1.16	2.16	1.12	2.32	0.65507	-0.01046	0.43182
Alien Bullets Hit	Game Performance	Small increase in user scores as ETHD speed increases	0.60	0.96	1.04	1.00	0.3666	0.6471	0.2974
Spaceship Damage	Game Performance	Small decrease in user damage taken as ETHD speed increases	6.44	6.00	6.40	6.12	-0.2101	-0.0584	-0.2012

the 10% speed profile to the others, with the results for the 40%, 70% and 100% being similar. These observations are consistent with the rig speed analysis seen in Section 3.7 where the average speeds for the 40%, 70% and 100% speed profiles are similar and much larger than for the 10% profile.

In general, it is not easy to identify large changes between speed profiles visually, with the exceptions for *Quality Of Interface* (Figure E.5) and *Alien Bullets Hit* (Figure E.28), and indicates that users were more sensitive to speed changes for these aspects than the others. There were some smaller but consistent effects that can be seen visually for *Total Aliens Hits* (Figure E.17), *Aliens Hit by Normal and Double Shots* (Figure E.20) and *Spaceship Damage* (Figure E.31). This could be due to the sample size of 25 being too low, users being exposed to each speed profile just once and there being too few possible ordinal values for the scale average score data. However, analysing the averages, data distributions and probabilities of final scores from OLR showed that there is a small effect on scores as the ETHD speed increases in most cases. Some of the scales had a few anomalies, where the scores would rise and then drop, which could be attributed to the fact that participants were only exposed to each of the speed profiles once, and possibly did not have enough time to become sufficiently confident with each one. Although the order of the speed profiles and the questions were randomised for each participant, those that the users were first exposed to could potentially contribute to an anchoring effect that resulted in these anomalies. When reviewing the values of these anomalies, it was noted that the effect sizes were small, and the differences between the anomaly values reported and the adjacent speed profile values were small and statistically insignificant.

For the PQ, both scales of *Possibility To Act* and *Quality Of Interface* demonstrated an increase in user scores for these components of immersion and presence when the ETHD speed was increased (see Table 5.5). OLR coefficients for the 40%, 70% and 100% speed profiles ranged from 0.09878 to 0.24734 for *Possibility To Act* and -0.00621 to 0.25914 for *Quality Of Interface*, indicating a tendency towards increasing mean scores compared to the 10% speed profile.

The UEQ results were more varied, with *Attractiveness* showing little effect as the ETHD speed was increased, and the OLR coefficients being very small, ranging from -0.04654 to 0.09177 in the order of 10^{-2} . *Efficiency* had a small increase in mean scores, with OLR coefficients ranging from -0.2395 to 0.2296. *Dependability* surprisingly had a small decrease in mean scores, with OLR coefficients ranging from -0.19617 to 0.01454.

All game performance categories demonstrated a small improvement in user scores as ETHD speed increased. *Total Aliens Hit* had OLR coefficients from 0.3715 to 0.4928, *Aliens Hit by Normal and Double Shots* had 0.3145 to 0.4471 and *Aliens Hit by Laser and Big Shots* had -0.01046 to 0.65507. *Alien Bullets Hit* had OLR coefficients from 0.2974 to 0.6471. The *Spaceship Damage* category had a small decrease in mean damage taken which is good for the player, with OLR coefficients from -0.2101 to -0.0584, indicating that participants could manoeuvre easily, as the responsiveness of the system allowed for quick changes in movement.

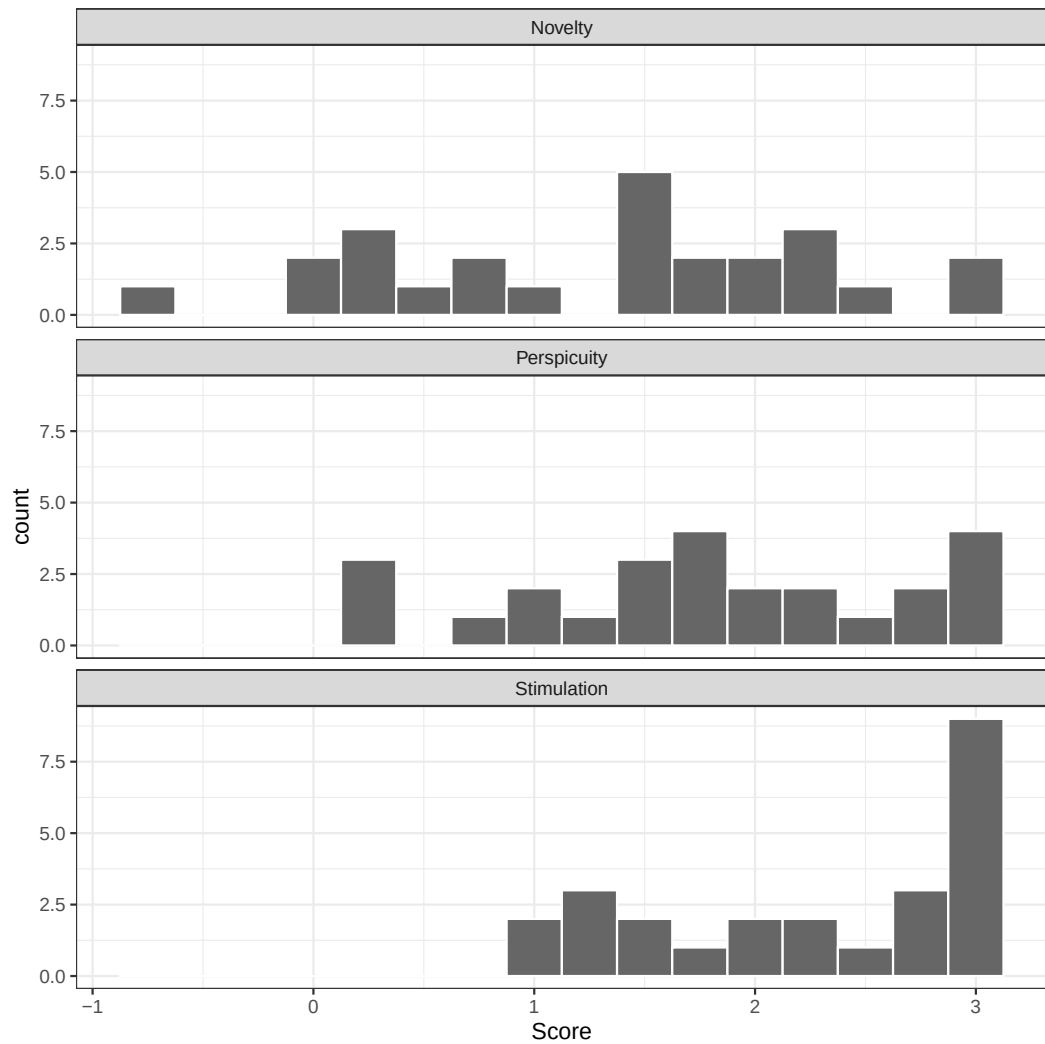


Figure 5.6: Final score frequencies for UEQ scales of *Perspicuity*, *Stimulation* and *Novelty*.

Table 5.6: Mean scores and standard deviation results for *Perspicuity*, *Stimulation* and *Novelty*

Scale	Mean	Standard Deviation
Perspicuity	1.79	0.883
Stimulation	2.27	0.750
Novelty	1.33	0.994

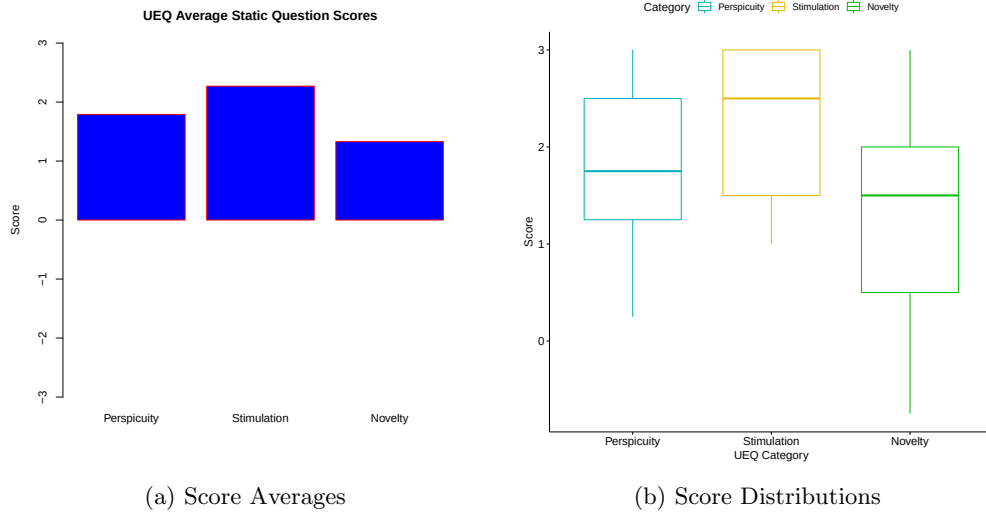


Figure 5.7: Score averages and distributions for the UEQ scales of *Perspicuity*, *Stimulation* and *Novelty*

5.4.3 Overall Sentiment Analysis

This section presents the results obtained for the UEQ scales of *Perspicuity*, *Stimulation* and *Novelty*, which were rated once only at the end of the experiment to obtain user sentiment on the experience as a whole. Each of these scales had four questions that when averaged with Equation 5.3, result in 25 possible ordinal score outcomes with an interval of 0.25 between values. These final score value frequencies for each scale are reported in Figure 5.6 for each speed profile. Means and standard deviations are summarised in Table 5.6, the score averages and data distributions being visualised in Figure 5.7. All score averages for *Perspicuity*, *Stimulation* and *Novelty* indicate positive sentiment in these scales, with the highest observed being for the *Stimulation* scale.

The probability density plot of the average scores for *Perspicuity*, *Stimulation* and *Novelty* in Figure 5.8 indicates that there are very low probabilities for negative

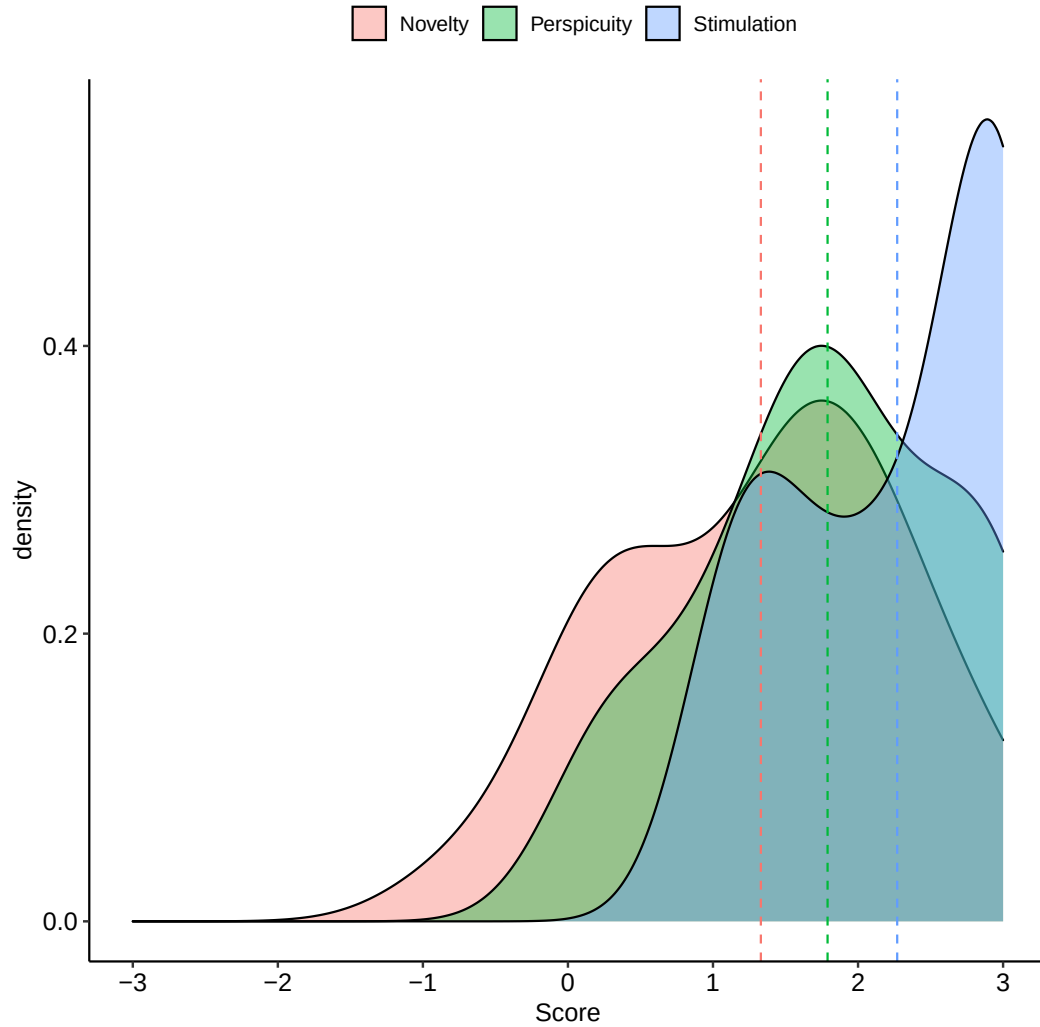


Figure 5.8: Probability density plot of average scores for *Perspicuity*, *Stimulation* and *Novelty*

sentiment, and where there was negative sentiment that it is very close to neutral.

Novelty had the lowest scores, but these still had mostly positive sentiments, with an average of 1.33, a few tending towards neutral sentiment and the rest having much more positive sentiment towards the experience. This can be seen in Figure 5.8, where the peaks of the probability density plot for *Novelty* lie between 0-2 for the scale score, and indicate that users have neutral to positive sentiment towards the new idea of using an ETHD for haptic feedback.

Perspicuity had the second highest average of 1.79, with all individual scale scores resulting in positive sentiment and a few tending toward neutral. Figure 5.8 indicates that the highest probabilities are noted for scores around the average value, with high probability of the maximum positive sentiment score of 3, which indicate that

users found the *Fast ETHD* system to be easy to understand. This also indicates that the training given to users was adequate in allowing them to perform their best when using the system.

Stimulation had the highest average of 2.27, with individual scale scores resulting in positive sentiment, and a few user scale scores resulting in the maximum positive sentiment score of 3, as indicated in Figure 5.8. This indicates that the experiment and the *Fast ETHD* system was a very exciting experience for some participants, this being the first VR experience for many users, let alone using haptic feedback, which shows clearly in the results.

5.5 Conclusions

RQ1 questions if users were able to perceive an increase in immersion, presence and UX when ETHD speed was increased, this experiment aiming to answer this question by gauging their responses to the PQ and UEQ, which categorised different components of the concepts of immersion, presence and UX, with Table 5.7 presenting a summary of the analyses.

Table 5.7: Summary of Results

Category / Scale	Type of Analysis	Comments
Possibility To Act	PQ Speed Variation	Small increase in immersion and presence scores as ETHD speed increases
Quality Of Interface	PQ Speed Variation	Small increase in immersion and presence scores as ETHD speed increases
Attractiveness	UEQ Speed Variation	Not much effect on UX scores as ETHD speed increases
Efficiency	UEQ Speed Variation	Small increase in UX scores as ETHD speed increases
Dependability	UEQ Speed Variation	Small decrease in UX scores as ETHD speed increases
Total Aliens Hit	Game Performance Speed Variation	Small increase in user scores as ETHD speed increases

Table 5.7 – continued from previous page

Category / Scale	Type of Analysis	Comments
Aliens Hit by Normal and Double Shots	Game Performance Speed Variation	Small increase in user scores as ETHD speed increases
Aliens Hit by Laser and Big Shots	Game Performance Speed Variation	Small increase in user scores as ETHD speed increases
Alien Bullets Hit	Game Performance Speed Variation	Small increase in user scores as ETHD speed increases
Spaceship Damage	Game Performance Speed Variation	Small decrease in user damage taken as ETHD speed increases
Novelty	UEQ Overall Sentiment	Neutral to positive sentiment
Perspicuity	UEQ Overall Sentiment	Clear positive sentiment
Stimulation	UEQ Overall Sentiment	Very positive sentiment

For speed variation analyses, the scores increased for the PQ aspects of *Possibility To Act* and *Quality Of Interface*, as well as the *Efficiency* aspect of the UEQ. User performance within the game improved in the *Total Aliens Hit*, *Aliens Hit by Normal and Double Shots*, *Aliens Hit by Laser and Big Shots*, *Alien Bullets Hit* and *Spaceship Damage* categories. No effect was observed on scores for the the UEQ aspect of *Attractiveness*, with a negative effect being observed for *Dependability*. No differences were found to be statistically significant, with all effect sizes being small, indicating that users were not sensitive to the range of speed profiles that they were exposed to. In future studies, it would be beneficial to expose users to a faster rig with a greater range of speeds, to more speed profiles and to each speed profile multiple times. This would lengthen the experiment procedure and would require further considerations around safety, but would allow users to become more familiar and sensitive to each speed profile, enabling them to provide more consistent ratings.

For the overall sentiment analyses on the UEQ scales, *Novelty* displayed neutral to positive sentiment on the system and the experience as a whole, *Perspicuity* displayed

clear positive sentiment on their clarity and understanding of the system, while *Stimulation* showed very positive sentiment on how interesting and exciting it was. Overall, their sentiment on the system and the experience as a whole was positive. Therefore, as a final answer to RQ1, the analysis indicates that overall, an increase in ETHD speed contributes to a small increase in user scores for immersion, presence and UX.

5.6 Chapter Summary

This chapter presented the VR Alien Shooter Game Experiment that was conducted to answer RQ1, its goal being to determine if an increase in ETHD speed resulted in an increase in immersion, presence and UX. To answer this question, participants had to play the VR alien shooting game as the ETHD speed profile was varied. They had to answer modified versions of the PQ and UEQ for each speed profile, and a final set of questions on the experience as a whole at the end.

Speed variation analyses was conducted on the questionnaire scale scores where those scale questions were answered by participants at the end of a round for a particular speed profile. Game performance was also analysed, with the speed variation analyses indicating that while differences were observed between speed profiles, none were statistically significant. Two out of the 10 components displayed no effect and a small negative effect on user scores as the ETHD speed increased, while the other eight components all displayed a small positive effect. Users were most sensitive to speed changes with regards to *Quality Of Interface* and *Alien Bullets Hit*, and to a smaller extent for *Total Aliens Hits*, *Aliens Hit by Normal and Double Shots* and *Spaceship Damage*.

Overall sentiment analyses on three of the UEQ scales indicated that participants had positive sentiment towards the system and the experience as a whole. Finally, it was concluded that, overall, an increase in ETHD speed results in a small increase in user scores for immersion, presence and UX, answering RQ1. This chapter focused on the concepts of immersion, presence and UX and answering RQ1.

The next chapter will discuss the concept of task performance and how to quantify it to answer RQ2.

Chapter 6

Literature Review: Task Performance

This chapter provides a literature review on the concept of task performance within the context of Human-Computer Interaction (HCI) situations. Fitts's Law, a model used to predict human movement towards a target, is outlined, as well as its formal application in the form of the multidirectional tapping task from the ISO 9241-9 and ISO/TS 9241-411 specifications. The metric determined from this test is throughput, with the standards for conducting the test to produce accurate results provided. A review of studies that have conducted this test in Virtual Reality (VR) with various setups is also given.

6.1 Introduction

Task performance can be defined as how effective assignees are at performing a given activity, with quantitative evaluation of devices used for these activities being important to gauge the benefits offered to the user in HCI situations [107].

6.2 Measuring Task Performance

The International Standards Organisation created the ISO 9241-9, and more recent ISO/TS 9241-411 specifications, to influence the design of interactive computer pointing devices, such as computer mice, joysticks and touch sensitive screens, with a focus on accommodating the user's comfort, safety and bio-mechanical capabilities and limitations [40, 48]. These specifications provide guidelines to optimise design on

these aspects, and also provide testing procedures to evaluate the devices to be used, which measure the three areas of *task performance*, *comfort* and *effort*.

Task performance measurements can be conducted using six tasks provided by ISO/TS 9241-411, a one-dimensional tapping task, a two-dimensional (2D) multidirectional tapping task, dragging, free-hand tracing, free-hand input with text or pictures and a grasp and park task. The widely used 2D multidirectional tapping task uses Fitts's Law to empirically determine the task performance of users as throughput measured in bits per second (bps). Targets in the ISO 9241-9 and ISO/TS 9241-411 specification for the 2D multidirectional tapping task are arranged in a circle, with users being meant to move between the targets in this arrangement in order to record the values needed to determine throughput.

Comfort is evaluated by using the Device Assessment Questionnaire (DAQ) provided by ISO 9241-9 and ISO/TS 9241-411. Users can assess the device interacted with by rating it according to the 13 questions in the DAQ, that address issues of physical operation, fatigue, comfort, speed, accuracy and overall usability. The assessment uses a 7-point Likert scale for each question to quantify the ratings.

Effort is evaluated by measuring the bio-mechanical elements of muscle load and fatigue, and is not usually evaluated since it requires specialised equipment.

The ISO 9241-9 and ISO/TS 9241-411 testing procedures have been used to evaluate numerous peripherals. Douglas *et al.* tested the performance and comfort of a touchpad and isometric joystick using the 2D multidirectional tapping task, and the DAQ, to evaluate the ISO 9241-9 specification itself, and determined that the evaluation of performance is reliable and can be used to successfully predict user behaviour [39]. The DAQ was determined to be too vague to pick up specific problems with a device, and they recommended adding additional open-ended questions.

Measuring task performance is important to determine how useful a product will be to the user, and in creating an ETHD, its usefulness must ultimately be determined, and whether or not it is needed at all to improve experiences in VR. Fitts's Law and the ISO 9241-9 and ISO/TS 9241-411 specifications have been used extensively to evaluate HCI devices, and would be useful in this study to determine the benefits of including an ETHD into a VR experience. If the proposed ETHD can produce similar or higher throughput to other effective setups for VR, this would positively re-assure its potential as an effective addition to the VR experience. Furthermore, comparisons can be done with other studies that employed the ISO 9241-9 or ISO/TS 9241-411 testing procedures.

6.3 Fitts's Law

Measuring task performance quantitatively is a way to effectively evaluate the usefulness of a device, with Fitts's Law being a well-established model used to predict human movement towards a target [108]. This model determines that the time taken to move towards a targeted area is related to the size of the target and the distance to it, its output being throughput, a single metric that combines speed and accuracy. Throughput, measured in bits per second (bps), is commonly used as a characteristic of pointing devices and can be used to compare devices quantitatively.

The ISO/TS 9241-411 2D multidirectional tapping task (also referred to as *Fitts's Test* in this study), which makes use of Fitts's Law, is depicted in Figure 6.1, showing the targets of the test arranged in a circle, with participants being required to click on the targets in a predefined sequence as fast and accurately as possible. Accuracy of a click is determined by how far away the click was from the centre of the target and therefore increases the closer the click is to the centre. The Index of Difficulty (ID), measured in bits, is the overall difficulty of a movement task, and is determined from the distance required to move towards a target (D) and the size of the target (W) (Equation 6.1). Movement Time MT is linearly related to ID (Equation 6.2), with the throughput (TP) being determined as the ratio of ID to MT (Equation 6.3).

$$ID = \log_2\left(\frac{D}{W} + 1\right) \quad (6.1)$$

$$MT = a + b \cdot ID \quad (6.2)$$

$$TP = \frac{ID}{MT} \quad (6.3)$$

By using multiple values of D and W in combination to achieve many values of ID , the movement time (MT) recorded from these movements can be used in linear regression methods to determine the overall throughput of a pointing device.

Measuring task performance is important to determine how effective an HCI device or setup will be to use. Computer mice, touchpads and joysticks have been evaluated using the ISO 9241-9 and ISO/TS 9241-411 tests, of particular interest being the measured throughput of the computer mouse, which has a throughput value ranging between 3.7bps to 4.9bps, and to which most other devices are compared to [39, 109].

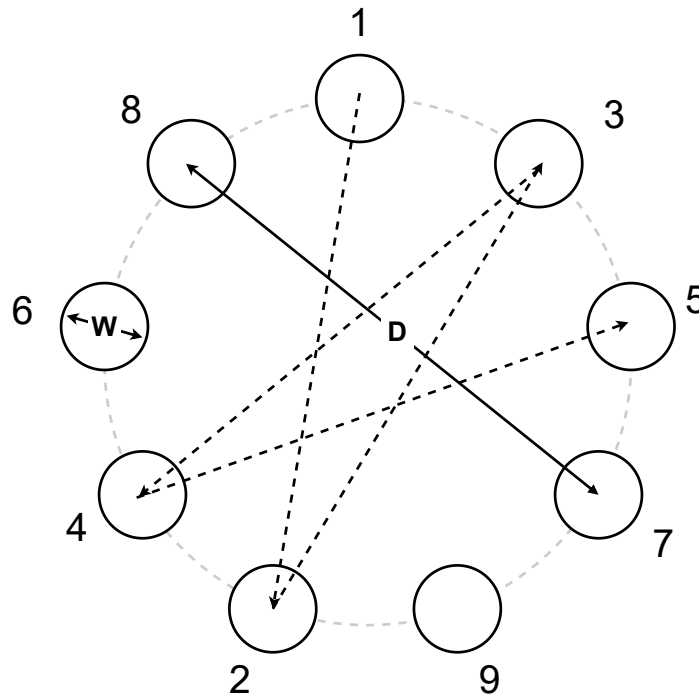


Figure 6.1: The ISO/TS 9241-411 multidirectional tapping task. Targets are arranged in a circle and must be clicked in a predefined order from 1-9. D is the distance between targets and W is the target width.

The modern touchscreen yields some of the highest throughput at approximately 6-6.85bps [110, 111].

6.4 Standards for Fitts's Law HCI studies

Previous studies on Fitts's Law have varied on how the tests were conducted, with older studies having collected, cleaned and analysed the data differently to current methods. Soukoreff and MacKenzie analysed many studies on Fitts's Law and provided guidance towards a standard for these tests [111, 112]. A summary of these recommendations is as follows:

- The Shannon formula should be used to calculate Index of Difficulty (ID) (Equation 6.1).
- An ID range of 2-8bits should be used, as this wide range is representative of most situations. Each ID condition should be presented to the user many

times, and Movement Time (MT) should be captured between the start and end positions of a movement.

- Measurements should be done for the scatter of movement end-point positions, for which error rates or recording the end-point positions would be sufficient.
- An *adjustment for accuracy* for each user for each condition needs to be done, with the error rates or end-point data being used to convert D , W and ID values into their *effective* forms of De , We and IDe .
- Linear regression must be done on the average Movement Time ($\overline{MT}$) and IDe data to determine goodness of fit, and to establish if the model verifies Fitts's Law predictions.
- The grand throughput of a device or experiment condition can be calculated via a mean of means of all $\overline{MT}$ and IDe data across all users and conditions. This grand throughput can be used for comparisons to other devices, conditions and setups.

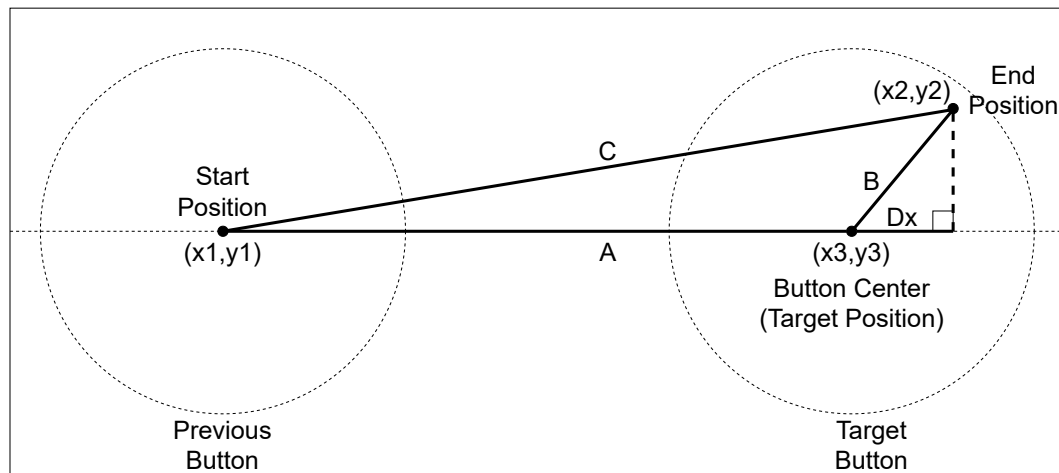


Figure 6.2: The geometry governing a movement from one target to the next

A movement's primary data consists of the movement time from start to finish, the start and end positions, and the position of the target button centre. As recommended by Soukoreff and MacKenzie, the *adjustment for accuracy* is performed using this data to get the transformed values for effective distance, De , and effective width, We , per subject, per condition. Looking at the geometry of the movement in Figure 6.2, the distance for A , B and C is first calculated, and are then used to calculate the effective distance from the centre of the target, Dx , and the effective distance travelled for the movement, Ae . A negative value for Dx indicates an undershoot, while a positive value indicates an overshoot.

$$A = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2} \quad (6.4)$$

$$B = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2} \quad (6.5)$$

$$C = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (6.6)$$

$$Dx = \frac{C^2 - B^2 - A^2}{2A} \quad (6.7)$$

$$Ae = A + Dx \quad (6.8)$$

De is the mean of Ae for n movements for a single user for one condition across all repetitions. The average movement time ($\overline{MT}$) is also calculated as the average movement time for a single user for one condition across all repetitions. SD_x is the standard deviation of Dx , which is used to calculate We . De and We are then used to calculate the effective Index of Difficulty IDe .

$$De = \frac{1}{n} \sum_{i=1}^n Ae_i \quad (6.9)$$

$$We = 4.133 \cdot SD_x \quad (6.10)$$

$$\overline{MT} = \frac{1}{n} \sum_{i=1}^n MT_i \quad (6.11)$$

$$IDe = \log_2\left(\frac{De}{We} + 1\right) \quad (6.12)$$

The IDe and $\overline{MT}$ pairs are then used to determine the intercept and gradient for Equation 6.2 as well as the grand throughput (GTP) (Equation 6.13). For y subjects and x conditions there are $y \times x$ pairs of IDe and $\overline{MT}$, this grand throughput being a means for comparisons with other devices and setups.

$$GTP = \frac{1}{y} \sum_{i=1}^y \left(\frac{1}{x} \sum_{j=1}^x \frac{IDe_{ij}}{\overline{MT}_{ij}} \right) \quad (6.13)$$

In addition to the grand throughput, Soukoreff and MacKenzie suggest that SD_x and error rate (ER) observations are provided for a complete picture. The error

rate is the ratio of missed button clicks to the total number of clicks per condition (Equation 6.14).

$$ER = \frac{\text{NoOfMisses}}{\text{TotalNoOfMovements}} \times 100 \quad (6.14)$$

6.5 Fitts's Law in Virtual Environments

Fitts's Law has worked well for evaluating traditional HCI devices and been used in studies to evaluate devices that are used for interacting with Virtual Environments (VEs). Teather *et al.* used the multidirectional tapping task to evaluate performance using passive haptic feedback in a Cave Automatic Virtual Environment (CAVE), where the VE is projected onto the walls of a room-sized cube [29]. The multidirectional tapping task test was displayed in the VE, in which subjects used a stylus to click on these targets in mid-air and on a transparent plastic panel positioned in front of them to provide passive haptic feedback. The throughput determined was 2.56bps for the haptics condition and 2.37bps for the no-haptics condition.

Joyce and Robinson conducted a similar experiment with users viewing the multidirectional tapping task test in a VE, the difference being that they clicked on its targets with their fingers [31]. This was enabled by using the Oculus Rift Development Kit 2 in conjunction with the Leap Motion Controller for hand tracking. Subjects touched targets in two separate conditions, one without any haptic feedback and one with a flat panel that was used to provide passive haptic feedback, with the no-haptics condition yielding a throughput of 4.1bps and with passive haptic feedback yielding 4.7bps. They also found that training time decreased with the haptic feedback and that users preferred the passive haptics to interact with, as they felt it helped them perform faster and more accurately, and increased their sense of presence.

Pino *et al.* used the Microsoft Kinect to allow their subjects to move a cursor on a monitor screen with their hands, with a click being recognised by the users vocalising a sound that was then identified by the Kinect's microphones [113]. The 2D multidirectional tapping task was used for the evaluation, and yielded a throughput of 2.1bps, while a modified 3D version of the task yielded 1.06bps.

Mutasim *et al.* used the HTC Vive Pro Eye headset with a Leap Motion Controller for hand tracking as well as the multidirectional tapping task to determine throughputs for three techniques of clicking, pinching and dwelling on targets, the highest

throughput being from the former, which yielded approximately 4bps [114].

6.6 Chapter Summary

This chapter presented a literature review on the concept of task performance in the context of HCI situations, and discussed the various methods of measuring task performance from the ISO 9241-9 and ISO/TS 9241-411 specifications. Fitts's Law is reviewed and the importance of determining a device or setup's throughput is emphasised for comparison purposes. The suggestions set out by Soukoreff and MacKenzie to standardise Fitts's Law studies for HCI were summarised and the calculations required for accurate throughput calculations were detailed. Finally, studies on Fitts's Law for VR are outlined, where a variety of throughput values are observed across many different experiment setups, with many using hand tracking for interactions. Some of these studies exposed subjects to conditions with and without haptics, but none attempted to determine the throughput of ETHD setups.

The next chapter will discuss the methodology of the VR Fitts's Test Experiment that was designed to answer RQ2, "*What task performance is achieved with a high-speed ETHD and how does it compare to zero-delay conditions and previous studies?*" The discussions from this chapter will be used to measure the task performance on the *Fast ETHD* system and other zero-latency conditions for comparison. The ISO/TS 9241-411 multidirectional tapping task will be used to determine the throughput of these conditions to answer RQ2.

Chapter 7

VR Fitts's Test Experiment Methodology

This chapter discusses the No Haptics, Table Haptics and ETHD Haptics Conditions that were planned for the VR Fitts's Test Experiment to answer RQ2, and details the experiment methodology which includes the equipment, software, and user interfaces used, data capturing, data transformations, sample size estimations, participant selection, experiment procedures and data analysis.

7.1 Introduction

The aim of an Encountered-Type Haptic Display (ETHD) is to make the Virtual Reality (VR) experience as realistic as possible by giving the user high quality dynamic haptic feedback. An effective ETHD will allow the user to perform tasks in the Virtual Environment (VE) using this feedback in such a seamless way that they would be tricked into thinking that the virtual world is real and responds to actions in real-time. The **VR Fitts's Test Experiment** was designed to answer RQ2, “*What task performance is achieved with a high-speed ETHD, and how does it compare to zero-delay conditions and previous studies?*”, by determining the throughput of the *Fast ETHD* system and comparing it to zero-latency conditions. This experiment consisted of three conditions that were treated as sub-experiments, all being conducted using the ISO/TS 9241-411 multidirectional tapping task to determine the throughput for different configurations of haptic feedback. Studies on providing haptics to the user in VR, such as those by Teather *et al.* and Joyce and Robinson, usually exposed participants to no-haptics and passive flat haptics

conditions [29,31]. The three conditions for the VR Fitts's Test Experiment included these, as well as a condition for ETHD haptic feedback. The three sub-experiments conducted for this study were labelled as the **No Haptics**, **ETHD Haptics** and **Table Haptics Conditions**. In order to answer RQ2, the grand throughput for each sub-experiment was calculated, followed by comparisons between their throughput to determine if the differences were significant. A comparison between the Table and ETHD Haptics Conditions was done as these varied only in the haptics method used, whereas the No Haptics Condition varied in a few more areas, due to it being a pilot experiment. A comparison between all three sub-experiments was therefore done separately, considering that the No Haptics Condition had more threats to validity.

The No Haptics Condition sub-experiment was conducted first as a pilot experiment to test the *VR Test* application on the Oculus Quest and determine throughput without any haptics. The ETHD Haptics Condition sub-experiment was conducted to test the haptics provided by the *Fast ETHD* system. The Table Haptics Condition sub-experiment was conducted as a control experiment to complement the ETHD Haptics Condition, as well as for comparison purposes, as done in previous studies. The Table Haptics Condition complemented the flat haptics conditions in previous studies and was an ideal zero-latency condition that could be used for comparison against the ETHD Haptics Condition, which had an inherent delay in its design.

The three sub-experiments all had a within-subjects design with regards to the Index of Difficulty values exposed to each participant, after which a between-subjects comparison was done for all three conditions on the throughput values that were calculated. All of the ISO/TS 9241-411 multidirectional tapping task experiments used common design components, and where possible, the designs were as similar as possible, with as few variations as possible to improve validity. The common components that were used in the design of the No Haptics, Table Haptics and ETHD Haptics sub-experiments are discussed in this chapter. These include the experiment methodology, equipment, software, user interfaces, data capturing, data transformations, sample size estimations, participant selection, experiment procedures and data analysis. Results from these experiments will then be presented in the following chapter.

7.2 Experimental Design

The ISO/TS 9241-411 multidirectional tapping task was implemented within the *VR Test* application for the Oculus Quest (Figure 7.1) (see Section 3.3.6 for more details

on the *VR Test* application). All of the sub-experiments used this application to determine task performance as throughput, with guidance on their designs being taken from the ISO/TS 9241-411 specification and the standards set out by Soukoreff and MacKenzie (see Section 6.4) [48, 111, 112].

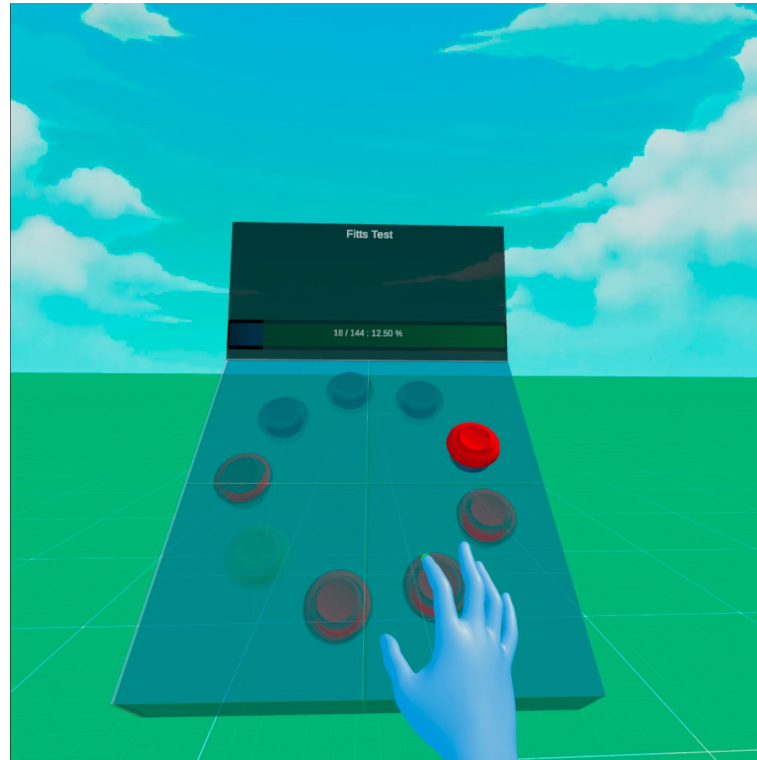


Figure 7.1: The *VR Test* application user interface for the No Haptics Condition angled at 45° .

A number of configurations of the ISO/TS 9241-411 multidirectional tapping task circle were determined from distances between buttons D and button widths W for each sub-experiment. When setting the circle diameter, it was important to remember that the target-to-target distance D , as seen in Figure 6.1 in Section 6.3, would be less than this diameter. An array of custom button models designed in Blender that matched the real world buttons in Figure 3.3 in Section 3.3.3 were used, as well as a pre-existing virtual arcade button model from the *HandsInteractionTrainScene* in the Oculus Sample Framework. The width of the button (W) was determined using the *Bounds* functionality in Unity, with the j values of D and the k values of W being used to determine $j \times k$ values of ID (Equation 6.1) [115]. This would normally result in a $j \times k$ Factorial Design, but the values of ID are the most important aspect of this experiment, as the final data used from the experiment would be MT and ID pairs (Table 7.1). Therefore the experiment was simplified to use a Single Factor Design with $j \times k$ values of ID as treatments (Table 7.2).

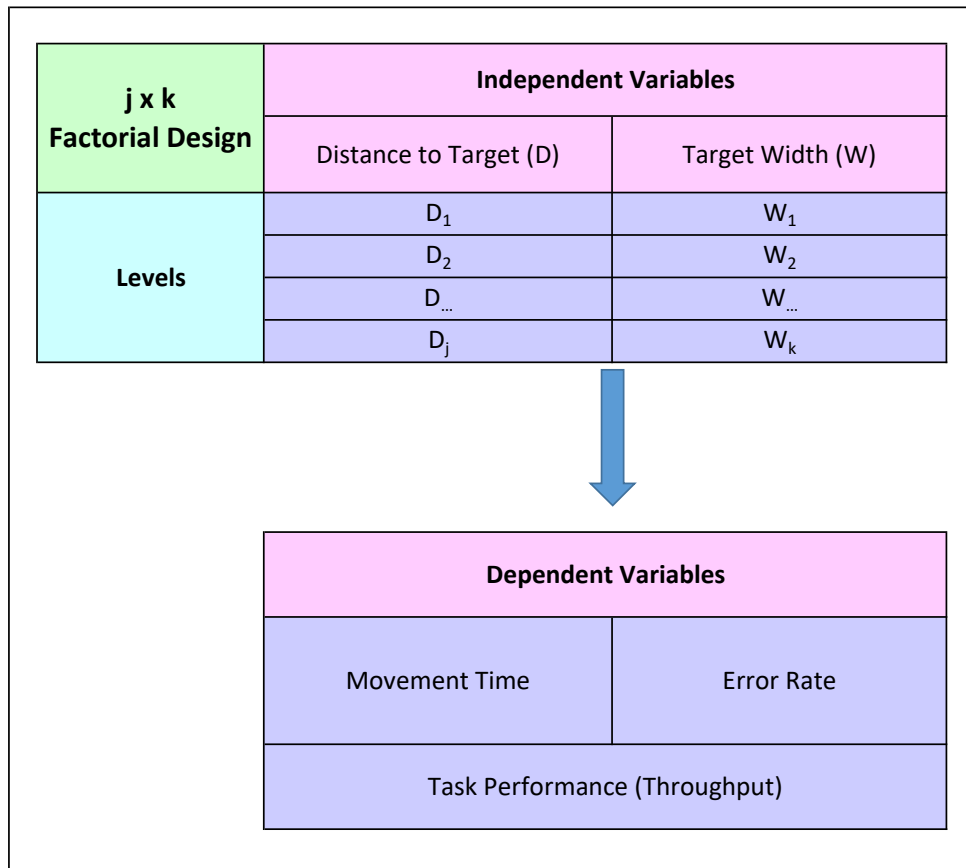


Table 7.1: The $j \times k$ factorial design for levels of D and W resulting in the dependent variables for movement time, error rate and throughput.

Soukoreff and MacKenzie suggest an ID range of 2-8bits, the lower ID values being simple to accommodate, but the higher values requiring either increasing D or reducing W (Equation 6.1) [112]. Making the circle too wide would have resulted in forcing the user to move their entire body to reach one end of the circle to the other, and reducing the button width to less than 2cm negatively impacted user experience in pilot studies. A typical user's fingertip is much larger than the button at these sizes, which is occluded by the user's finger, these being defined as the *fat finger problem* and the *occlusion problem* respectively [116]. The D and W values and the resulting values for ID were chosen for each ISO/TS 9241-411 multidirectional tapping task sub-experiment taking into consideration the limitations for each condition. For all conditions, the button widths were in the same range but the Table and ETHD Haptics Conditions were limited to the sizes of the actual real world buttons, whereas for the No Haptics Condition, the virtual buttons could be scaled to any size. The target-to-target distances were limited by how much a participant's arm could reach in the No Haptics Condition and by how far the ETHD could reach for the Table and ETHD Haptics Conditions.

Single Factor Design	Independent Variable			Treatment
	D	W	Index of Difficulty (ID)	
Levels	D ₁	W ₁	ID ₁	A
	D ₁	W ₂	ID ₂	B
	D ₁	W _{...}	ID ₃	C
	D ₁	W _k	ID ₄	D
	D ₂	W ₁	ID ₅	E
	D ₂	W ₂	ID ₆	F
	D ₂	W _{...}	ID ₇	G
	D ₂	W _k	ID ₈	H
	D _{...}	W ₁	ID ₉	I
	D _{...}	W ₂	ID ₁₀	J
	D _{...}	W _{...}	ID ₁₁	K
	D _{...}	W _k	ID ₁₂	L
	D _j	W ₁	ID ₁₃	M
	D _j	W ₂	ID ₁₄	N
	D _j	W _{...}	ID _{...}	O
	D _j	W _k	ID _{j × k}	P

Table 7.2: The simplified single factor design for ID treatments arising from D and W levels.

A Randomised Complete Block Design was implemented for these sub-experiments (Table 7.3), with subjects being required to go through all $j \times k$ configurations per block. Three blocks were implemented for all configurations and are presented sequentially in a randomised order. A single circle configuration was treated as an individual trial for this study, with the circle consisting of n buttons for n movements per trial (n is configurable within the *VR Test* application to allow for different practise and full test designs). Subjects were required to click on all solid red highlighted buttons that appeared in the order specified in Figure 6.1 and to avoid the transparent buttons and control panel surface in Figure 7.1. The first button click started the timer for the user to complete the trial, their being required to click all buttons in the sequence presented as fast and accurately as possible. If a button was missed and the user touched the control panel surface or a transparent button instead, the panel would flash red and the next button in the sequence would be highlighted.

Randomised Complete Block Design		Block		
		1	2	3
Trial	1	C	H	E
	2	I	D	A
	3	D	I	F
	4	G	M	K
	5	J	B	N
	6	H	J	B
	7	K	N	L
	8	N	L	J
	9	P	F	D
	10	M	C	O
	11	L	O	P
	12	O	K	M
	13	A	P	I
	14	E	G	G
	15	F	A	C
	16	B	E	H

Table 7.3: The Randomised Block Design used for the different configurations of *ID*.

Keeping the arm in mid-air and continuously moving it around for long periods of time is strenuous and induces fatigue. Therefore, after a trial was completed, a message appeared next to the first button to indicate to the subject that they could take a short break if required to reduce fatigue.

The user started the application with both virtual hands in view but then made a choice for their dominant hand, after which it was in use, while the non-dominant hand was removed from the user's view so that they could focus on the single virtual hand. The application was designed in such a way that collision detection with the buttons and control panel surface could only be triggered with the index finger of the chosen dominant hand. A small green sphere on the tip of the index finger was a visual cue to the user to only use that finger.

The *VR Test* application created for this test supports different circle configurations, for which the distances, button widths, number of buttons and number of blocks can be set, which enabled different sequences for a practise round and the main test.

The practise round was important for the subjects to become familiar with interacting with the VR environment, clicking on the buttons correctly, following the pattern of

highlighted buttons and understanding how a miss affected the flow of the test. This was important as all users were novices and some had never been exposed to VR at all prior to this study. Soukoreff and MacKenzie suggest that subjects need to have enough training to ensure that they reach expert levels of performance before attempting the full test. Given the time constraints, shorter practise rounds were configured for each sub-experiment to expose subjects to enough movements and circle configuration variation to help them get to an acceptable level of performance before starting the proper test. The practise round also reduced the learning effects that were not considered for this study and allowed the test to be completed quicker before it became too monotonous and started to affect their motivation to complete the test correctly.

7.3 Equipment

The *Fast ETHD* system was used for the ETHD Haptics Condition to provide realistic haptic feedback to the user with a small amount of delay (see Chapter 3 for more details on the *Fast ETHD* system). This included the ETHD, the *QuestG2CoreBridge* control software and the *VR Test* application on the Oculus Quest headset. For the No Haptics and Table Haptics Conditions, only the Oculus Quest headset with the *VR Test* application was used.

7.4 User Interface

The control panel in the *VR Test* application could be configured to be tilted at certain angles. Many previous studies such as those by Teather *et al.* and Joyce and Robinson had the button panel interface more or less parallel to the user at 90° to the ground. The control panel for this study was angled at 45° for the No Haptics Condition (Figure 7.1) and 0° for the ETHD and Table Haptics Conditions (Figure 7.2). For the No Haptics Condition, users adjusted the control panel to be in line with their view, the 45° preventing users from having to bend their necks excessively (as would be the case if it were flat at 0°) and reduced arm fatigue from holding their arms in mid-air (as would be the case if it were facing the user directly at 90°). For the ETHD and Table Haptics Conditions, users had very minimal arm fatigue due to the haptic feedback given to them. However, the 0° angle of the control panel would have meant more bending of the neck, which was prevented by

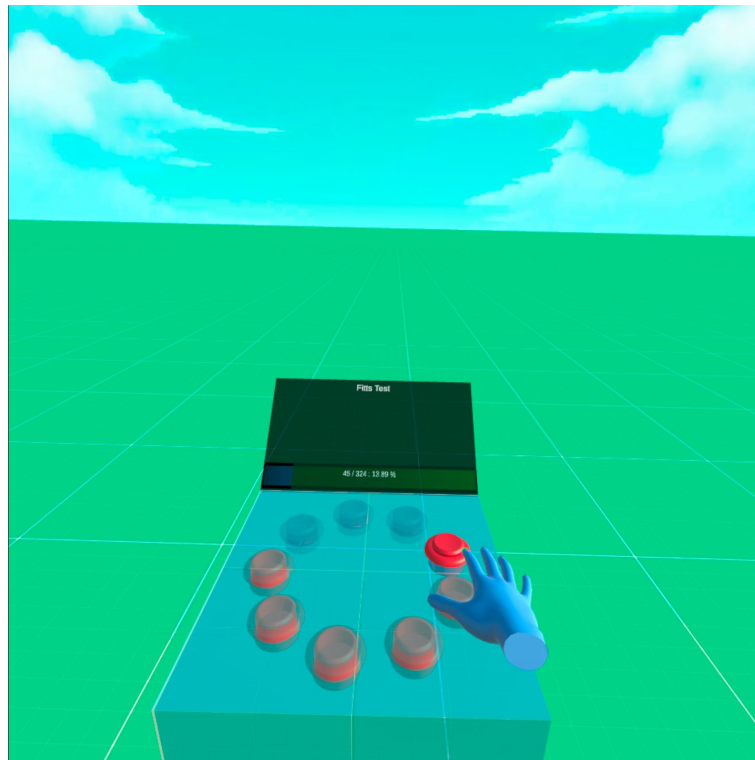


Figure 7.2: The *VR Test* application user interface for the Table Haptics and ETHD Haptics Conditions angled at 0° .

reducing the angle between the user and the control panel by propping up the ETHD table on bricks.

The interface moved through various ‘scenes’ for user help text, data input and training, some common scenes being used to adjust height calibration, input the dominant hand, gender and age choices, as well as the multidirectional tapping task (referred to as the “Fitts’s Test” scene within the application). These scenes all had different button layouts and help text, with the user being given the choices of ‘Right’ and ‘Left’ for the dominant hand choice scene. For the gender choice scene, the options of ‘Male’, ‘Female’ and ‘Choose not to say’ were available to select from. Buttons labelled from zero to nine were shown for the age input scene, with a ‘Reset’ button to erase what had been entered in case of a mistake and an ‘OK’ button to confirm the entered data. The user was given a practise round scene before moving on to the main Fitts’s Test scene, both of which cycled through different configurations of the multidirectional tapping task.

7.5 Data Capturing

The *VR Test* application captured the dominant hand, gender and age entered by the user into memory as well as the data for the practise and main Fitts's Test rounds. Each movement's start, end and target button centre 3D positions were captured as well as the movement time between start and end positions. The data for each circle configuration, including distance between targets, target width and expected Index of Difficulty were also captured. Unique identifiers for the movement, trial, block and user were also captured to determine the final throughput calculations. Finally, the index fingertip position, distance travelled, movement time and velocity for every point in a movement's trajectory was captured. The hand tracking rate on the Oculus Quest is lower than its display refresh rate so only unique trajectory positions were captured as they were updated.

Upon completion of the test, the above data was saved in an XML file on the Quest's on-board storage, with the practise round data being excluded. Supplementary files with a flat XML format for the movement, trajectory and circle configuration data were also saved for easier data extraction in the statistical analysis software.

7.6 Data Transformations

Soukoreff and MacKenzie's suggestions from Section 6.4 are used in this study to obtain accurate results that can be reliably compared to other studies. The *adjustment for accuracy* was done on D , W and ID values to convert them to De , We and IDe . The average movement time ($\overline{MT}$) values paired with the corresponding IDe condition values were then used to determine the grand throughput of the condition using Equation 6.13.

7.7 Sample Size Estimation

To obtain accurate results, *a priori* power analysis was first conducted to determine a sample size for each sub-experiment that would yield accurate results for the grand throughput calculations and comparisons between haptics conditions.

To avoid the Type I error of incorrectly rejecting the null hypothesis H_0 when it is actually true (Table 7.4), the probability of detecting a Type I error, the significance

Table 7.4: Conditions leading to accept or reject the null hypothesis H_0 .

	H_0 is actually true	H_0 is actually false
Test results accept H_0	Correctly accept H_0 <i>Probability</i> = $1 - \alpha$	Incorrectly accept H_0 (Type II error) <i>Probability</i> = β
Test results reject H_0	Incorrectly reject H_0 (Type I error) <i>Probability</i> = α	Correctly reject H_0 <i>Probability</i> = $1 - \beta$

level α , is chosen to be the commonly used value of 5% (0.05).

To avoid the Type II error of incorrectly accepting the null hypothesis when it is actually false (Table 7.4), the probability of detecting a Type II error, β , is chosen to be the commonly used value of 20% (0.2). By choosing this value, the power $1 - \beta$ is 80% (0.8), which is the probability of correctly rejecting the null hypothesis when it is actually false.

After the multidirectional tapping task was completed, the resulting IDe and $\overline{MT}$ pairs were plotted and fitted using linear regression to obtain the grand throughput and to show the relationship observed between these sets of data. Cohen's formulae on sample size, effect size and power for linear regression were used to get the minimum number of participants required for each sub-experiment for a power of 0.8 and a significance level of 0.05 [117].

$$f^2 = \frac{R^2}{1 - R^2} \quad (7.1)$$

Guidance was taken from the University of North Dakota's *Sample Size Calculation with R* document by Dr. Mark Williamson, which summarised the use of various power analysis techniques in R [103]. For linear regression, Cohen defined an effect size f^2 of 0.1 to be small, 0.25 to be medium, and 0.4 to be large (Equation 7.1). For linear regression, the *pwr.f2.test* function in R was used, where the numerator degrees of freedom u is set to 1. Using a medium effect size with the above significance and power levels gives the denominator degrees of freedom $v = 31.42944$, and rounding it off to the next whole number and adding 2 (for the number of variables) gave the sample size of 34.

For the grand throughput calculations, this was a small requirement, as recording a user's IDe and MT data is cheap in terms of time requirements, where each

movement usually lasts under a second. Many errors were also encountered during the Fitts's Test in the form of misses, which required data cleaning to be performed. A sample size of 34 would last less than a minute for each participant and not allow for a broad range of ID values, which is specified as necessary from Soukoreff and MacKenzie [112]. Thus for grand throughput calculations, a much larger sample size needed to be collected, which was determined by the number of ID values and the number of participants.

The first comparison between only the Table and ETHD Haptics Conditions, was to determine if the throughput outcomes for these were significantly different. These conditions were purposefully designed in such a way that the only difference in factors was the type of haptic feedback given. An unpaired two sample t-test (or for non-parametric data, the Wilcoxon rank sum test) was regarded as adequate to compare the throughput outcomes for these conditions.

For the second comparison, all three conditions of No Haptics, Table Haptics and ETHD Haptics were tested for a significant difference. The reason that this comparison was separate and not tested exclusively is that the No Haptics Condition was viewed as a pilot experiment and had differing factors. A One-Way ANOVA (or for non-parametric data, the Kruskal-Wallis test) was sufficient to compare the data for these three conditions.

$$d = \frac{|m2 - m1|}{\sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}}} \quad (7.2)$$

Cohen's d uses differences in means of populations to determine effect size (Equation 7.2), with a small effect size being $d = 0.2$, a medium 0.5 and a large 0.8. Means and variances from the study by Teather *et al.* are provided for no haptics and haptics conditions [29]. For the no haptics condition the throughput mean was 2.37bps(SD 0.74) and for the haptics condition it was 2.56bps(SD 0.76), and as this study made use of similar conditions, it was appropriate to use the data to expect a certain effect size. Using this data with Equation 7.2, a value of 0.2533108 was calculated for the effect size d indicating a small to medium effect size.

Using this value of d as well as the above significance and power levels in sample size calculation for an unpaired two sample t-test yields a sample size of 245.605 per haptics condition group when using the *pwr.t.test* function in R [103]. This sample size indicates the number of participants required for the study to get the individual throughput values needed for analysis. This would be expensive in terms of time

requirements, as 30 to 60 minutes would be required for each participant. Running the calculation for a large effect where $d = 0.8$ yields a more manageable sample size of 25.52458, rounded off to 26 participants, per group (Figure 7.3). This sample size also corresponds to similar studies done using the ISO/TS 9241-411 multidirectional tapping task, e.g. Joyce and Robinson [31].

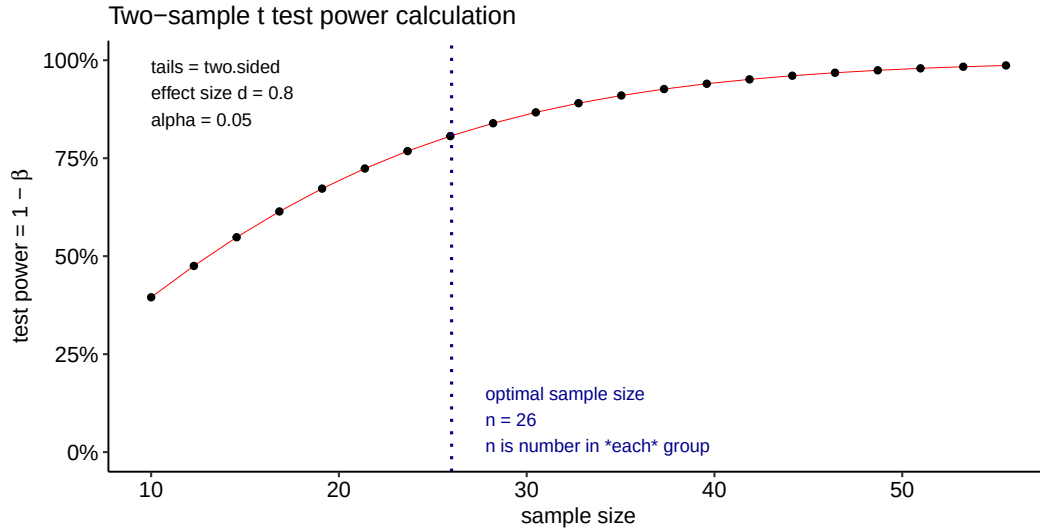


Figure 7.3: Sample size estimation for a t-test between the Table Haptics and ETHD Haptics Conditions.

When the standard deviations of 0.74 and 0.76 from the study by Teather *et al.* are used in Equation 7.3 for the difference in means (derived from Equation 7.2), a large effect size would equate to a difference in means of 0.6bps. However, after the pilot experiment with the No Haptics Condition (mean of 3.70bps, SD 0.476), a large effect size would now equate to a difference in means of 0.3808, which is a much more granular resolution to compare the means for the Table and ETHD Haptics Conditions [43]. A medium to large effect is expected to be observed, as inherent delays in the ETHD experiment setup decreased the throughput compared to the Table Haptics setup, where there were no delays. A sample size of 26 per group was therefore the minimum target sample size for the comparison between only the Table and ETHD Haptics Conditions.

$$|m_2 - m_1| = d \sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}} \quad (7.3)$$

For the second comparison, all haptics conditions were tested for a significant difference, with the One-Way ANOVA method being used. The effect size for a

One-Way ANOVA, Cohen's f , is suggested to be 0.1 for a small effect, 0.25 for a medium and 0.4 for a large. Following the effect size chosen for the first comparison, a large effect size of 0.4 was used for the value of f (Equation 7.4). Using the *pwr.anova.test* function in R, the sample size per haptics condition group determined is 21.10364, rounded up to 22 participants per group [103].

$$f = \sqrt{\frac{\sum_{i=1}^k p_i (\mu_i - \mu)^2}{\sigma^2}} \quad (7.4)$$

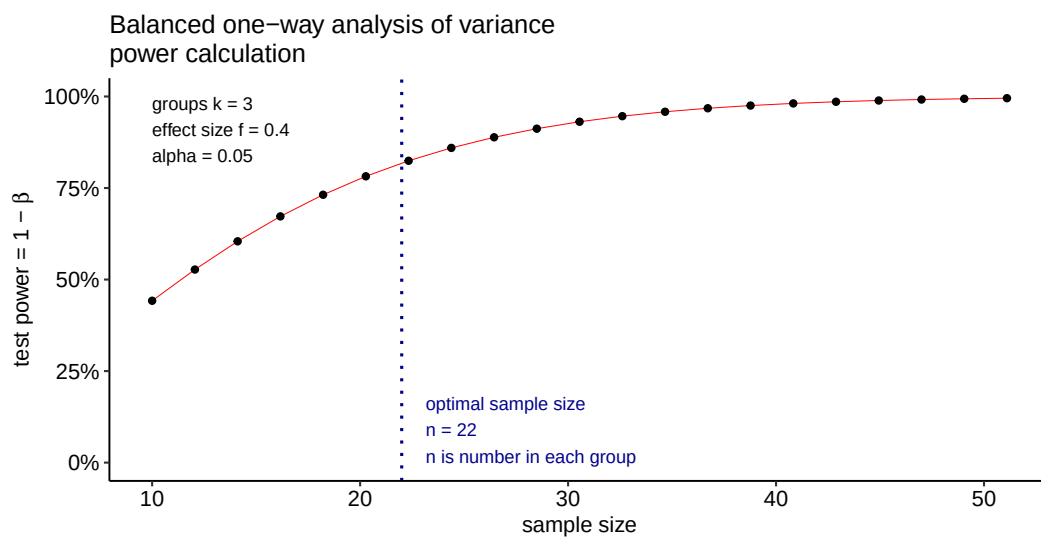


Figure 7.4: Sample Size Estimation for a One-Way ANOVA between No Haptics, Table Haptics and ETHD Haptics Conditions.

From the above calculation, an accurate t-test for the Table Haptics and ETHD Haptics Conditions required a minimum sample size of 26 participants per group. An accurate ANOVA test for the No Haptics, Table Haptics and ETHD Haptics required a minimum of 22 participants per group. Therefore, the Table Haptics and ETHD Haptics experiments need a minimum of 26 participants and the No Haptics Condition requires a minimum of 22 participants. Previous ISO 9241-9 studies with similar experiment designs by Joyce and Robinson, Teather et al. and Douglas et al. utilised 12 to 24 subjects respectively [29, 31, 39]. This number of subjects produced 7776 to 18000 recorded movements, which for these experiments was in line with previous similar studies.

7.8 Experimental Procedure

All experiments were conducted within the Chamber of Mines building located on the University of the Witwatersrand premises. Due to the Oculus Quest’s requirement of good lighting conditions for optimal hand tracking, suitable well-lit locations were chosen. The location also had to have enough space for the subject to move around without bumping into anything. The Oculus Quest has a built-in “Guardian” system that allows setting up a virtual safety perimeter to prevent users bumping into any real world objects, such as walls, and following its configuration allowed subjects to be prepped to take part in the experiment.

An open invitation for participation was made to all students and staff at the School of Electrical and Information Engineering at the University of the Witwatersrand via staff and student email lists, and posters that were put up around the building. Those who responded were requested to meet and were verbally briefed on the procedures and aims of the experiment, and asked to read a Participant Information Sheet (see Appendix D) with more details. If they wished to proceed with the experiment, they were required to sign a consent form. All users had their arm temperature checked with an infrared thermometer to make sure they did not have a fever, and declare that they were not displaying any symptoms of Covid-19. Thereafter, they were shown how to fit the Oculus Quest comfortably with a clear view of the VE.

For the initial calibration phase, two methods were used, the No Haptics condition entailing subjects being prompted in-app to adjust the position of the control panel with the Oculus Touch controllers for their height, and to be a comfortable distance from their body to be able to interact with it. For the ETHD and Table Haptics conditions, a manual alignment of the virtual control panel to the rig control panel, and a test run through a modified practise round to test the responsiveness of the button clicks was done before handing it over to the participant (see Section 3.6.2 for more information on the calibration of the *Fast ETHD* system). Thereafter, the subject saw virtual representations of their hands and used them as interaction devices, being informed to click on the virtual arcade buttons with their index finger. They were then prompted in-app to enter in their dominant hand, gender and age, after which the practise round began, with the first button of the trial informing them to take a break if they became tired. After the practise round, they proceeded to perform the full multidirectional tapping task, with both the practise round and the proper test having a progress bar that indicated the completion percentage and how many movements had been completed.

A final scene indicated completion of the experiment and advised the user to call the researcher to help them take off the headset, after which the final scene was checked for visual confirmation of when all files containing the subject's captured data had been successfully saved onto the device. The subject was then thanked for their participation, and while they did not receive any direct benefits and were all willing volunteers, those who completed the experiment were offered further time to familiarise themselves with the device through pre-loaded games.

7.9 Participants

Participants aged 18 years and older were welcomed to take part in the experiment, had to be in good health and be physically able to participate. As members of the School, participants needed to be familiar with using computers or video games for work or entertainment so as to ensure appropriate levels of hand-eye coordination that were required for the experiments.

7.10 Errors and Data Reduction

Each participant went through three blocks of $j \times k$ configurations, with each configuration consisting of nine movements, resulting in $3 \times j \times k \times 9$ movements being captured per person. Movements were flagged to indicate if the user missed the target and to indicate having low hand tracking confidence at any point in its trajectory using the functionality from Oculus [118]. Low confidence could arise from poor lighting, users obstructing the view of the Oculus Quest's cameras by blocking one hand with the other, holding the hand flat and perpendicular to the cameras so that no individual fingers can be distinguished, or moving too fast.

Hand-tracking errors due to less than ideal lighting conditions did not have much effect on a user's target-to-target movement data. However, these errors did contribute to spikes in velocity and distance travelled in the trajectory data that were not possible by human means, while hand tracking errors due to user hand gestures did contribute to responsiveness issues. Users were advised before starting the test to keep their palm open and click only with their index finger by moving their entire hand downward to click, as seen in Figure 3.10a, as this provided optimal hand tracking. More details on hand tracking and examples of poor tracking are in Section 3.6.3.

Target misses sometimes had a significant effect on target-to-target movement data (Figure 7.5), with most misses due to the user moving most of the distance towards a target and missing it by a small distance, and occurred fairly frequently for the smallest button widths. However, as mentioned by Soukoreff and MacKenzie, subjects can sometimes double click on a target which registers a successful click for the current target but a miss for the next [112]. This was observed for a number of subjects who tried to click a button multiple times to make sure that the target button was clicked. This type of error creates a movement data capture that indicates very low distance travelled and a very high effective button width, which resulted in an extremely low *ID* value and a very short movement time. The movement following the double click was also very short, as the new target was adjacent to the user's current position. Leaving in these errors skewed the results, as there appeared to be an extra distance close to zero, which contributed to the circle configurations.

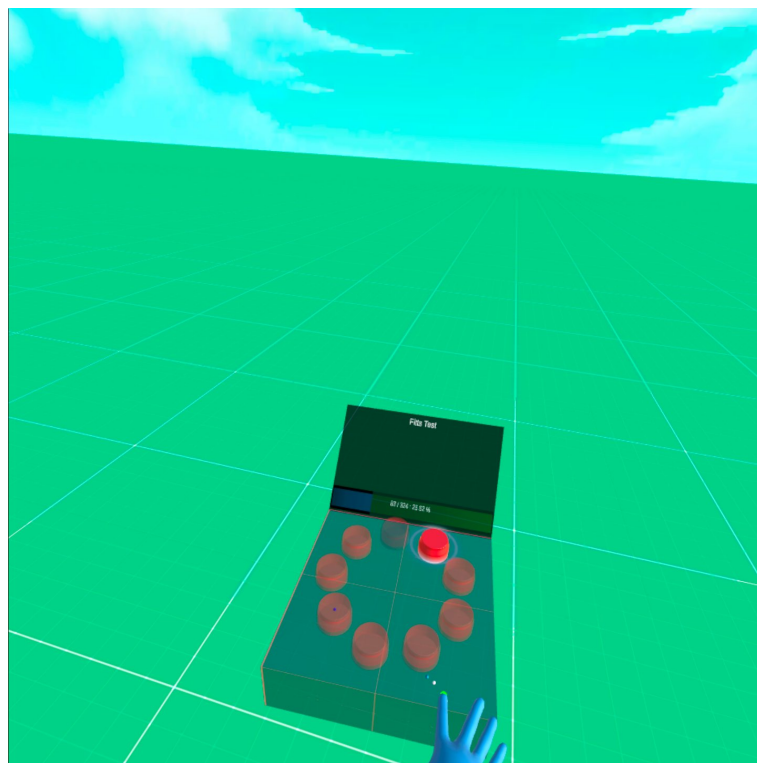


Figure 7.5: Clicking on the control panel or a transparent button registers as a miss. The table flashed red and the application moves onto the next target to visually indicate the miss to the user.

Some subjects also took much longer to complete the test, taking their time instead of rapidly moving, which was required for the multidirectional tapping task. Some may have even been taking a break in the middle of a trial, which resulted in movement times that were far off from the average. When an error such as the double click miss

mentioned above occurred, almost impossibly low movement times were recorded.

In summary:

- Some pointing hand gestures caused hand tracking errors that increased movement times.
- Too short movement times indicated double click misses.
- Longer times indicated that the user took their time instead of clicking targets rapidly.
- Too short distances travelled indicated double click errors.
- Too large distances from the button centre indicated that the user's aim towards the target deviated too much.
- A double click error could create a movement with an extremely small distance value and an extremely large button width value resulting in a very low *ID* value.

Soukoreff and MacKenzie advised that trials in which final movement distance or time is more than three standard deviations away from the average should be investigated, and if deemed to be outliers should be removed. Based on the factors above, the recommendations from Soukoreff and MacKenzie were extended to filter data on movement times, distance travelled and distance from the button centre on a per condition basis for this study.

As the Effective Index of Difficulty *ID_e* values were calculated on a per user per condition basis, Joyce and Robinson only deemed a condition for a user to be valid if at least one third of the total movements per condition remained after the initial data cleaning process [31]. This step was also performed on the data sets for each sub-experiment after cleaning for movement times, distances travelled and distances from the button centre. The complete end-to-end captured movement data was used, with homing and dwell time not being applicable for this study, as the user is constantly moving from target to target and not required to hover within the vicinity of the target [112].

7.11 Data Analysis

After performing the adjustment for accuracy to get the IDe values from the target-to-target endpoint data, Soukeroff and MacKenzie advise to plot the IDe and $\overline{MT}$ pairs and use linear regression to determine if the fit is good, indicating that Fitts's Law does apply to the data [112]. Tests for linearity, normality and homoscedasticity (homogeneity of residuals variance) on the data for IDe and $\overline{MT}$ were done to determine if the parametric Pearson correlation test could be used to analyse the correlation or the non-parametric Kendall correlation test. Guidance for these tests was taken from www.sthda.com and other online resources focused on statistical data analysis in R [119–124]. The *Residuals vs Fitted* regression plot was used to check for linearity of the data, and the Shapiro-Wilk normality test, as well as density and Q-Q (Quantile-Quantile) plots, were used to test for normal distribution of the data. The Breusch–Pagan test and *Scale-Location* plot was used to test for the homoscedasticity of the data, while the correlation coefficient from the Pearson or Kendall test was be used to indicate the effect size (0.1 is small, 0.3 is medium, and 0.5 is a large correlation) [104].

Soukeroff and MacKenzie also recommend analysing the intercept for the movement time and to explain any large intercept values, and advised calculating the grand throughput from all IDe and $\overline{MT}$ pairs using Equation 6.13. As per their recommendations, average movement times, error rates and standard deviation of end-point positions SD_x per condition were also included to give an overall picture of the data.

After the grand throughput outcomes and analysis for each of the No Haptics, ETHD Haptics and Table Haptics sub-experiments were concluded, further comparisons were done to compare the results. A direct between-subjects comparison for the ETHD and Table Haptics was done using individual user throughput outcomes, as these experiments were designed to limit variations to only the haptic feedback methods. A further between-subjects comparison was made between all three sub-experiment conditions, while noting that the No Haptics experiment was done as a preliminary pilot study with extra variations that could be a threat to validity. Finally, the grand throughput outcomes for all three experiments was compared to previous studies on Fitts's Law for VR, haptic feedback and other pointing devices.

7.12 Chapter Summary

This chapter discussed the No Haptics, ETHD Haptics and Table Haptics sub-experiments that implemented the ISO/TS 9241-411 Multi-directional tapping task. The experiment design, equipment and data capturing were discussed, followed by the adjustment for accuracy data transformations, sources of errors and the data cleaning necessary to get correct results. A sample size estimation was done to determine how much data is needed to ensure significant results, with a minimum of 34 movements per participant required for grand throughput calculations, 26 participants for a t-test comparison between the Table and ETHD Haptics Conditions, and 22 participants for the One-Way ANOVA comparison between all haptics conditions. The experiment procedure with participants was then presented, followed by the analysis of the data and final results procedure to be used on each condition's captured data, which tested linearity, normality and homoscedasticity of the data to determine if parametric or non-parametric comparison tests could be used. The following chapter will discuss the specific variations, observations and results of these experiments.

Chapter 8

VR Fitts's Law Experiment Results

This chapter provides the observations and results obtained from the No Haptics, Table Haptics and ETHD Haptics Conditions to answer RQ2. The methodology described in Chapter 7 was applied to the *ID* and *MT* data to get error rates, accuracy, movement times and throughput per condition. Discussions on this calculated data are provided as well as comparisons between haptic conditions and with device setups from previous studies.

8.1 Introduction

This chapter discusses a study that investigated novice human performance using the hand tracking capabilities of the Oculus Quest with varying implementations of haptic feedback. Of particular interest are the results obtained from the *Fast ETHD* system and how it compares to the other haptic feedback methods to answer RQ2, “*What task performance is achieved with a high-speed Encountered-Type Haptic Display (ETHD) and how does it compare to zero-delay conditions and previous studies?*” The ISO/TS 9241-411 multidirectional tapping task in the form of a virtual button pressing application was implemented, and the human performance measured in a single metric called throughput, in bits per second (bps), that combines speed and accuracy. The metrics for error rates, accuracy and movement times and movement trajectory analysis were also assessed. Three sub-experiments were conducted, varying in the way that haptic feedback was provided to the user, being referred to as the **No Haptics**, **ETHD Haptics** and **Table Haptics Condition** sub-experiments. A total of 76 people participated, 27 participants in the ETHD Haptics Condition, 26 for the Table Haptics Condition and 23 for the No Haptics Condition. Comparisons were made between the results of the three experiments and the results obtained

from previous Fitts's Law studies, with suggestions being made on how to improve the design of ETHD systems to optimise latency.

8.2 No Haptics Condition

The first sub-experiment, the No Haptics Condition, focused on users doing the multidirectional tapping task in mid-air with no haptic feedback, and was initially conducted to test the *VR Test* application developed for the Oculus Quest to aid this study. Due to the lack of haptic feedback, users had to click through a virtual button until an audible click sound effect was triggered to indicate a successful click (Figure 8.1). This sub-experiment was used as a pilot study to test the accuracy of the application and collect data that would be used to design the final experiments on the Table and ETHD Haptics conditions to ensure that they would be as accurate as possible. The results from this study were published in the proceedings for the South African Institute for Computer Scientists and Information Technologists (SAICSIT) 2021 conference under the entry titled *Determining Human Hand Performance with the Oculus Quest in Virtual Reality Using Fitts's Law* [43].

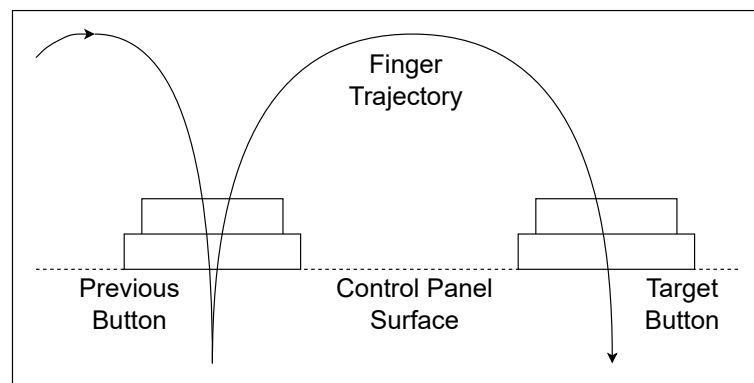


Figure 8.1: Finger trajectory over time with no haptics.

8.2.1 Equipment

The No Haptics experiment consisted of participants only using the Oculus Quest headset, the only software being the *VR Test* application running on the Quest, which allowed the user to interact with a virtual interface. The Oculus Quest's high-accuracy controllers were used for the initial calibration of the experiment so

that users could interact with the test application interface comfortably, according to their height requirements.

8.2.2 User Interface

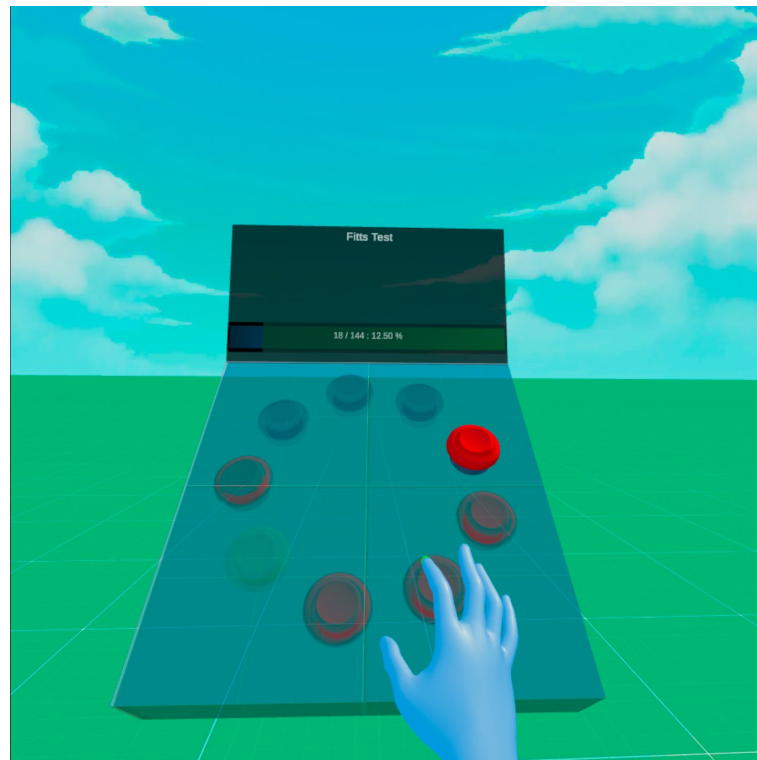


Figure 8.2: The multidirectional tapping task application user interface for the No Haptics Condition.

The control panel of the *VR Test* interface is angled at 45° so that users do not have to bend their necks excessively as depicted in Figure 8.2 (see Section 3.3.6 for more details on the application). The interface moved through the ‘scenes’ for height calibration, inputs for dominant hand, gender and age choices, and the multidirectional tapping task. The user was given a practise round scene before moving on to the main Fitts’s Test scene and final completion scene. Both these scenes cycled through the 16 different configurations of the multidirectional tapping task.

Table 8.1: Circle configurations of the multidirectional tapping task for the No Haptics Condition

<i>Diameter(mm)</i>	<i>D(mm)</i>	<i>Button Scale</i>	<i>W(mm)</i>	<i>ID(bits)</i>
200	197	0.5	22	3.322
200	197	1.0	44	2.460
200	197	1.5	66	2.000
200	197	2.0	88	1.701
400	394	0.5	22	4.248
400	394	1.0	44	3.322
400	394	1.5	66	2.808
400	394	2.0	88	2.460
500	492	0.5	22	4.555
500	492	1.0	44	3.615
500	492	1.5	66	3.088
500	492	2.0	88	2.728
600	591	2.0	22	4.808
600	591	2.0	44	3.858
600	591	2.0	66	3.322
600	591	2.0	88	2.955

8.2.3 Experimental Design

Sixteen configurations of the ISO/TS 9241-411 multidirectional tapping task circle were determined from four distances and four button widths, which were determined by changing the Unity scale on an existing virtual arcade button model from the *HandsInteractionTrainScene* in the Oculus Sample Framework. The width of the button W was then determined using the *Bounds* functionality in Unity [115]. These four values of D and four values of W determine 16 values of ID (Equation 6.1). Table 8.1 presents the chosen range of 1.701-4.808bits which made the experience challenging while maintaining comfort. Subjects were required to go through all 16 configurations per block, which were presented sequentially in a randomised order. One circle configuration is treated as a single trial for this study and consists of $n = 9$ buttons for 9 movements per trial. Subjects were required to click on all solid red highlighted buttons that appear in the order specified in Figure 6.1, and to avoid the transparent buttons and control panel surface in Figure 8.2.

The practise round consisted of the user going through all 16 conditions for a single

block, with the circles consisting of seven buttons from which seven movements arise, which exposes the subject to a total of 112 movements to become familiar with before moving on to the main test.

The full test employs a $3 \times 4 \times 4$ within-subjects design, with the user being required to go through combinations of the four distances and the four button widths for a total of 16 conditions in a randomised sequence per block, which entailed three of these blocks. The circles for the full test consist of nine buttons from which nine movements per trial arise, which results in 432 total movements recorded per user.

8.2.4 Experimental Procedure

The experiment was conducted within the Chamber of Mines building located on the University of the Witwatersrand premises. A location in an open area within the building was chosen where it was well-lit by natural light. The location had enough space for the subject to move around without bumping into any walls or objects.

The subjects were first assisted to fit the Oculus Quest comfortably and then handed the controllers to set the initial calibration scene, which required them to adjust the position of the control panel for their height in-app to ensure a comfortable distance from their body. Once this step was completed, the subject passed the controllers back to the researcher and began reading the instructions and entering their age, gender and dominant hand data. The practise round then began, followed by the main test.

The average time spent within the application was 17 minutes, the fastest being 12 minutes and the slowest 31. Initial setup time including explanations, signing consent forms and fitting the Oculus Quest, took around 5-10 minutes, the full experiment taking an average of 25-30 minutes.

8.2.5 Participants

The minimum sample size for the No Haptics Fitts's Test was determined to be 22 participants (Section 7.7), the 23 volunteers consisting of 13 males and 10 females. Three of the volunteers were left-handed, and their average age was 29, with a range of 18 to 63 years. All participants were able-bodied and had no impairments that would have hindered their test results, some wore spectacles, and as they all had little to no experience with VR, were regarded as novice subjects.

Table 8.2: Metrics per ID before data cleaning for the No Haptics Condition

i	$ID(bits)$	$D(mm)$	$W(mm)$	$ER(\%)$	$\overline{MT}(ms)$	$SD_x(mm)$
1	1.701	197	88	4.19	759	39
2	2.000	197	66	4.51	772	42
3	2.460	394	88	4.99	911	75
4	2.460	197	44	14.81	785	58
5	2.728	492	88	6.76	1068	98
6	2.808	394	66	8.21	949	93
7	2.955	591	88	8.05	1285	134
8	3.088	492	66	11.92	1059	125
9	3.322	591	66	12.88	1182	164
10	3.322	394	44	20.29	980	120
11	3.322	197	22	31.40	831	79
12	3.615	492	44	19.48	1076	152
13	3.858	591	44	20.77	1121	207
14	4.248	394	22	36.07	948	157
15	4.555	492	22	36.23	1092	204
16	4.808	591	22	38.32	1254	245

8.2.6 Data Reduction

A total of 9936 movements were captured (23 subjects x 3 blocks x 16 trials x 9 movements per trial). The data cleaning process was then performed as described in Section 7.10. Starting with 9936 recorded movements and 368 potential pairs of IDe and $\overline{MT}$ for each condition across all users, a final total of 5394 valid movements for 271 pairs of IDe and $\overline{MT}$ values remained for analysis.

8.2.7 Data Analysis

All calculations were done on a per user per condition basis after cleaning the data. An increase in ID resulted in an increase in error rate ER and error in accuracy SD_x as seen in Table 8.2. Average movement time $\overline{MT}$ was mostly affected by the distance component D , while ID values were ordered from least to most difficult and labelled as condition i . Some circle configurations resulted in the same values of ID , which is why these are repeated in certain instances, but due to being different ultimately yielded unique results.

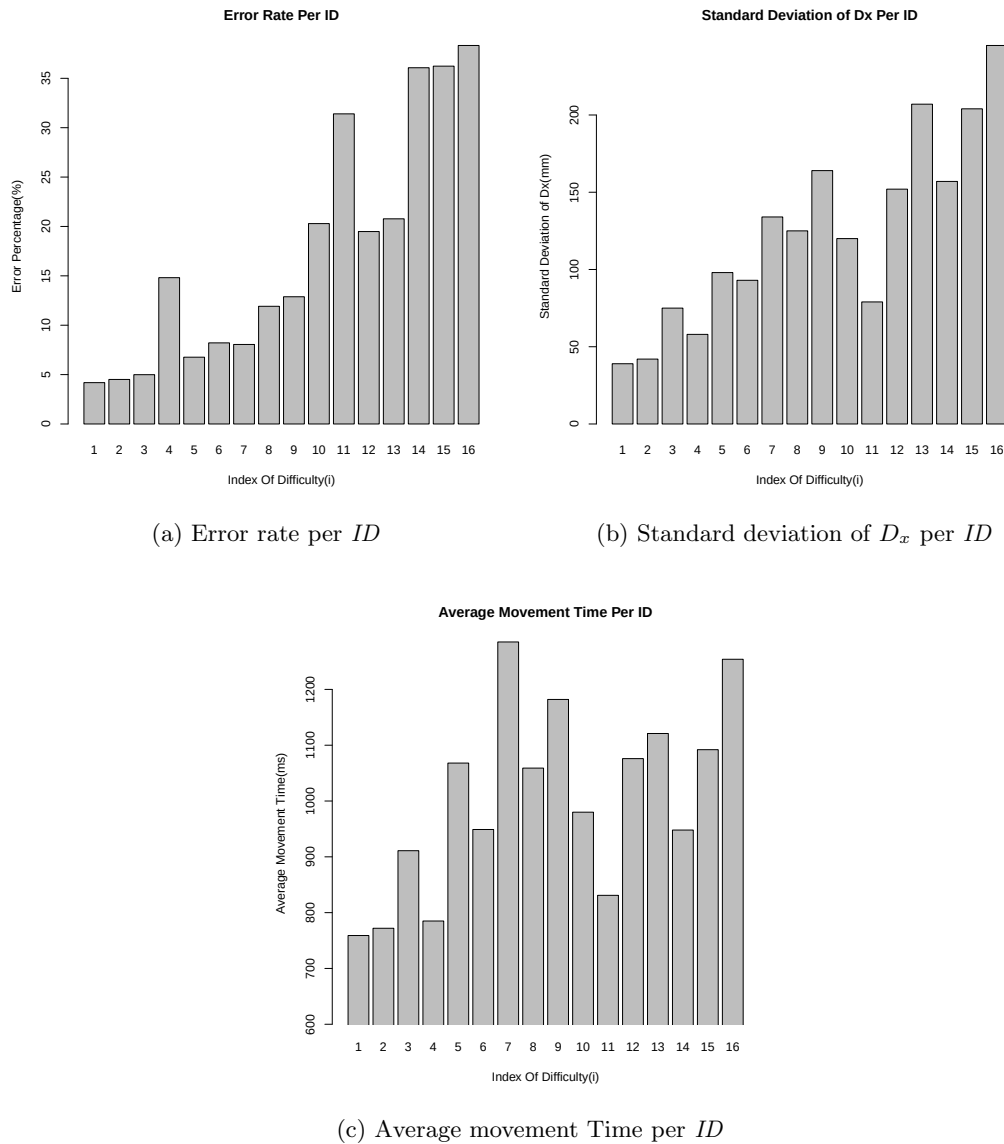


Figure 8.3: Average movement times, error rates and accuracy per ID for the No Haptics Condition.

Figure 8.3a shows that as the ID increased, so did the error rate, but that it was not perfectly ordered, despite the increasing values of ID . The noticeable spike in error rate for $ID_{i=4}$ was mainly due to the smaller value of W at 44mm, and is observed again for $ID_{i=11}$ for the smallest value of W at 22mm. The largest error rates were observed when the button width was the smallest at 22mm for $ID_{i=11}$, $ID_{i=14}$, $ID_{i=15}$ and $ID_{i=16}$. Smaller button widths appear to have a larger effect on error rates than larger distances do.

The error in accuracy SD_x was also observed to increase with increasing ID in

Figure 8.3b, with a noticeable exception being for $ID_{i=11}$, which consisted of the smallest distance and button width. For a larger button width, the subject can ‘cheat’ by deliberately clicking anywhere between the edge of the button and the centre instead of aiming for the centre [112]. A smaller button width would in theory increase accuracy, as even if the subject clicks on the edge of the button, the accuracy registered for We would be much better than clicking on the edge of a larger button. Larger distances and ID values increase the error in accuracy even if the button width was kept small, as seen in Figure 8.3b. However, for the case of $ID_{i=11}$, the smaller distance to travel and small button width allowed for easier targeting of the button and thus better accuracy.

Movement time appears to have been affected mainly by D , as observed in Figure 8.3c, that $ID_{i=7}$, $ID_{i=9}$, $ID_{i=13}$ and $ID_{i=16}$ all had the largest D value at 591mm, contributing to the largest average movement times. $ID_{i=5}$, $ID_{i=8}$, $ID_{i=12}$ and $ID_{i=15}$ at the second largest value of D at 492mm contributed to the next four largest average times and so forth.

8.2.8 Throughput Analysis

A least-squares linear regression was used to determine if there was a linear relationship between MT and ID .

The Q-Q and density plots for the IDe and $\overline{MT}$ data in Figure 8.4 indicate that the data roughly follows a normal distribution, with the Shapiro-Wilk normality test results for IDe giving $W = 0.98656$ and $p\text{-value} = 0.01183$, indicating that the data did not follow a normal distribution since $p\text{-value} < 0.05$. For $\overline{MT}$ the results were $W = 0.98282$ and $p\text{-value} = 0.002276$, indicating again that this data did not follow a normal distribution, and that the test for normality does not pass [119].

In the Residuals vs Fitted plot in Figure 8.5, the blue line mainly follows the horizontal dashed grey line, the assumption being that the relationship between the predictor IDe and the outcome $\overline{MT}$ is a linear one.

In the Scaled-Location plot in Figure 8.5, the blue line mainly follows a horizontal pattern with equally spread out data points, which indicates that the data passes the homoscedasticity test. To confirm this, the Breusch-Pagan test gives the result of $BP = 6.1053$, $df = 1$, $p\text{-value} = 0.01348$, and as the $p\text{-value}$ is less than 0.05, it can be concluded that this regression model violates the homoscedasticity assumption [124].

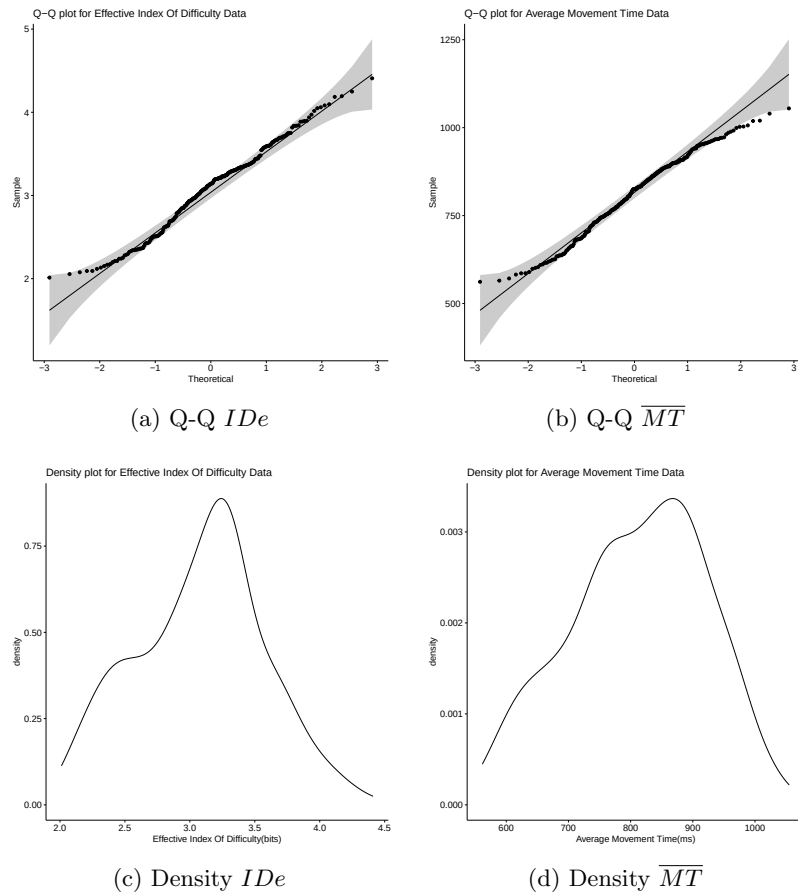


Figure 8.4: Q-Q and density plots for IDE and $\overline{MT}$ data for the No Haptics Condition

Due to the tests for normality and homoscedasticity failing, the non-parametric Kendall correlation test was used, the results being $\tau = 0.3544812$ and $p\text{-value} = 2.2 \times 10^{-16}$ [123]. The $p\text{-value}$ was less than the significance level of 0.05, and it can therefore be concluded that IDE and $\overline{MT}$ are significantly correlated, the correlation coefficient of 0.3544812 indicating a medium effect size.

Finally, it can be seen in Figure 8.6 that movement time increased with increasing ID after cleaning the data, with the intercept being at 447ms. Soukoreff and MacKenzie noted as a rough guideline that the intercept should lie between -200ms and 400ms, this being for expert subjects [112]. However, the subjects were regarded as novices for this study, as the practise round was limited, and did not advance them to expert status before the main test was conducted. It could also be attributable to the fact that much larger distances were used for this test, requiring more time for movement (compared to distances travelled for a mouse in pixels) or the lower 30Hz sampling of the hand tracking on the Oculus Quest.

In addition, no cleaning of the trajectory data was performed. When users click a

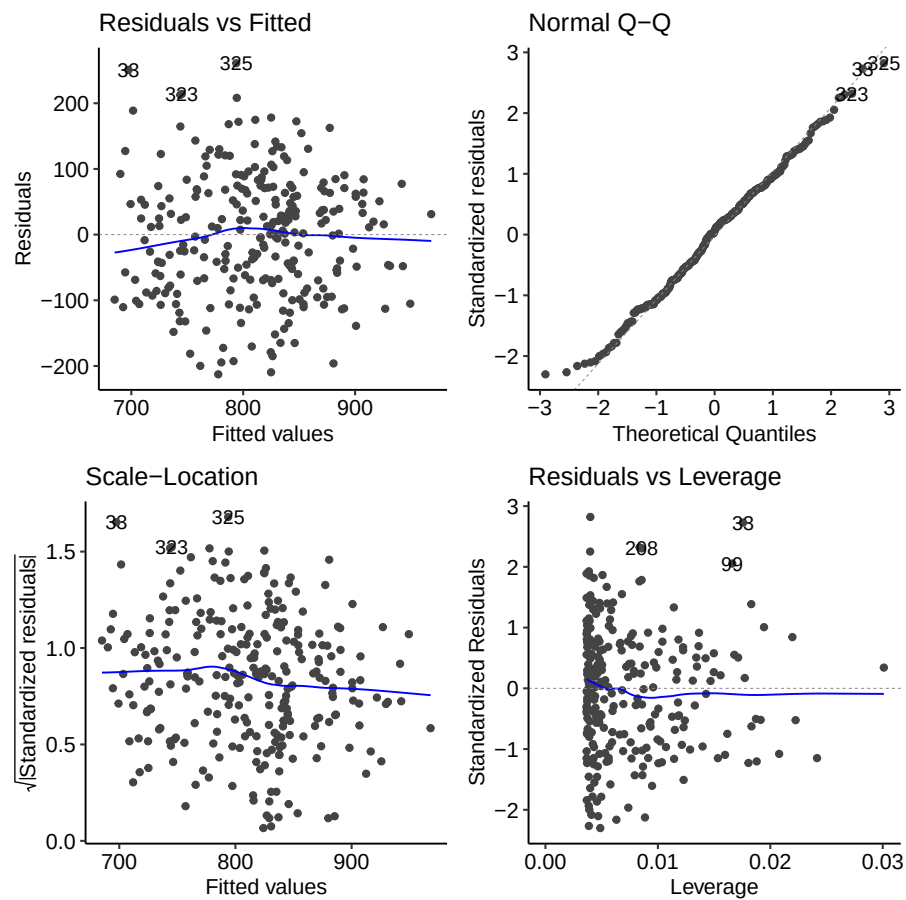
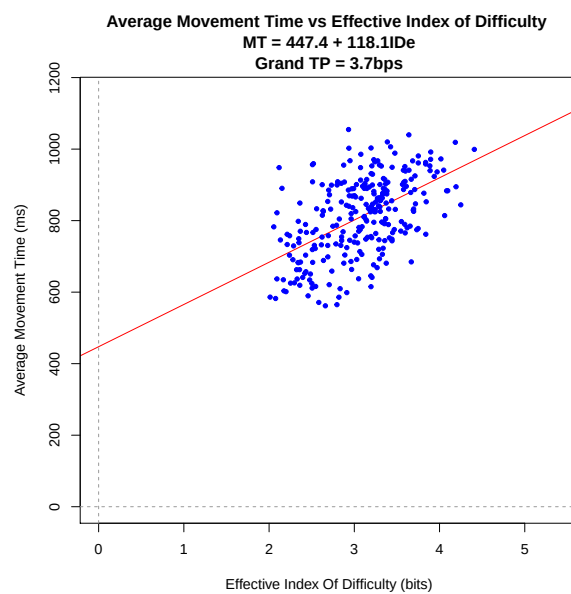


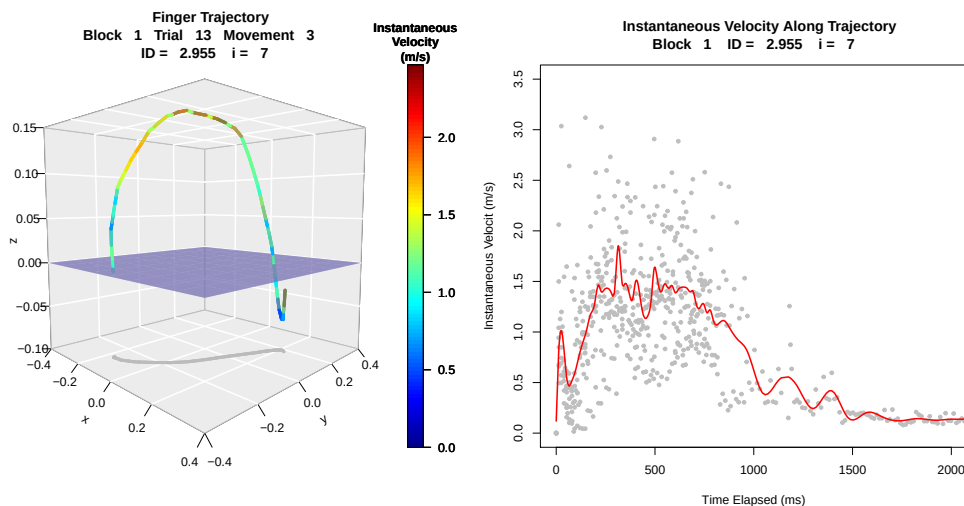
Figure 8.5: Plots on residuals for the No Haptics Condition

Figure 8.6: Average Movement Time vs Effective Index Of Difficulty IDe for the No Haptics Condition

button, their hand goes straight through the button and immediately activates the next target, as indicated in Figure 8.1. Extra time is sometimes taken to slow down and reverse direction to the next target after a successful click on the current button, which slightly increases the movement times. This extra movement is indicated below the plane of the control panel surface in an example recorded trajectory in Figure 8.7a. It was considered for removal from the trajectory data as reaction time, as occurred in the study by Soukoreff and MacKenzie, but as it only results in a very small increase in movement time, it was left in [112]. The full movement was also much more useful for comparisons to the movements for the Table and ETHD Haptics Conditions.

Using the average of the effective Index of Difficulty values $\overline{IDe} = 3.081bits$, the standard error of the intercept was $311.68ms$. The large F-statistic and low p -value indicate that the regression model $MT = 447.4 + 118.1IDe$ is a statistically significant fit for the data ($F_{1,271} = 108.2$, $p\text{-value} < 2.2 \times 10^{-16}$). The minimum recorded throughput for a user was 2.78bps and the maximum 4.48bps, with the grand throughput for the No Haptics Condition being 3.7bps.

8.2.9 Movement Trajectory Analysis



(a) A typical finger trajectory for a single movement relative to the control panel plane (b) The typical velocity profile for movement trajectories

Figure 8.7: An example of movement analysis for the No Haptics Condition.

As the subject's finger continues to move after clicking a target, the velocity profile of a movement trajectory will never be stationary at the beginning. It will always

start at a non-zero velocity, reduce as the user changes direction, and then accelerate towards the next target, slowing down again to click the target accurately. As a result of the subject's finger going through the button, the final velocity of the movement is again low but non-zero, as indicated in Figure 8.7b, and is similar to the velocity profiles plotted by Joyce and Robinson, which was plotted from velocity data across all movements for a single trial for a subject [31].

8.3 Table Haptics Condition

The next sub-experiment (referred to as the Table Haptics Condition) focused on the users performing the multidirectional tapping task on a flat table, which provided static passive haptic feedback, this being minimal, as it can only provide the smooth texture of the flat table. This experiment is also used as a control condition for the ETHD Haptics Condition, with all factors being the same except for the haptic feedback method.

For this experiment, users pushed their fingers into the button until they felt the table (Figure 8.8), with this physical sensation, as well as the audible click sound effect, indicating to users that the click had registered and that they could proceed to the next target. While the haptic feedback in this experiment is not very realistic, it maintains instant feedback with no delays between button clicks, as with the No Haptics Condition. Furthermore, the table surface prevented the extra movement following the button click, as observed in the No Haptics Condition, thereby reducing movement time.

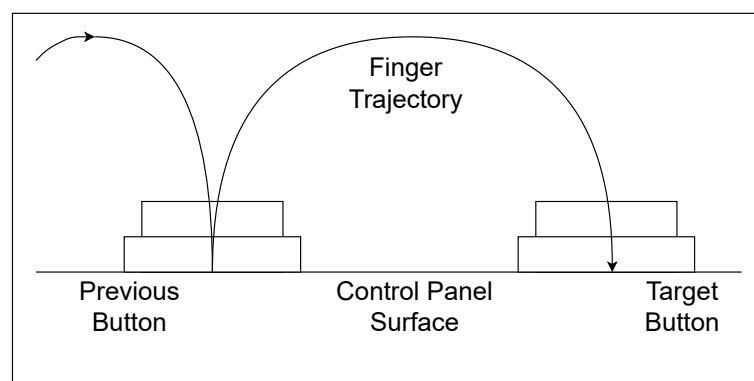


Figure 8.8: Finger trajectory over time with passive flat haptics.

8.3.1 Equipment

The Table Haptics sub-experiment entailed participants using only the Oculus Quest headset and a flat table with a smooth surface for passive haptic feedback, the only software needed being the *VR Test* application running on the Quest. The Oculus Quest's high-accuracy controllers are used for the initial calibration of the experiment so that the height position for the plane of the virtual blue table aligns to the physical height position of the table (Figure 8.10). The table was propped up on bricks so that it was raised to facilitate easier user interaction. The height of table surface from the ground was 95cm, this being done to match the interaction surface height of the ETHD (Figure 8.9).



Figure 8.9: The table used for the Table Haptics Condition.

8.3.2 User Interface

The *VR Test* application for the Oculus Quest was used for interactions with the virtual interface, with the control panel being angled at 0° (parallel to the table), requiring users to look slightly downwards at the table (Figure 8.10). The interface moved through 'scenes' for calibration of the virtual and physical height positions, dominant hand input, gender and age choices, and the multidirectional tapping task.

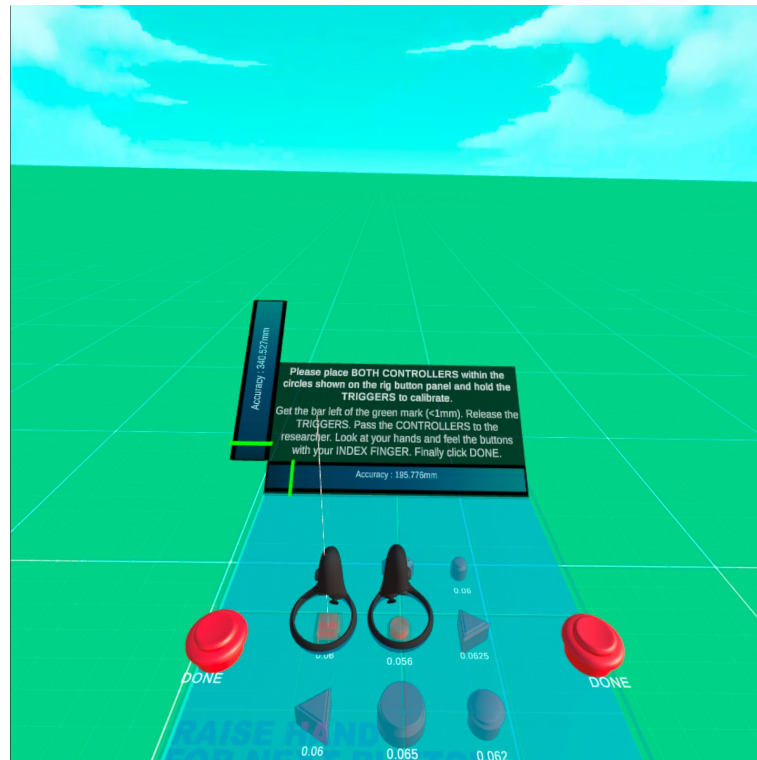


Figure 8.10: The *VR Test* application user interface for the Table Haptics Condition, this calibration scene being used to align the virtual table height to the physical table height.

The user was given a practise round scene before moving on to the main Fitts's Test scene and final completion scene. The practise round consists of the user being exposed to two configurations of the multidirectional tapping task for the largest distance and the smallest and largest button widths, while the main test cycles through 12 different configurations of the task.

8.3.3 Experimental Design

Twelve configurations of the ISO/TS 9241-411 multidirectional tapping task circle were determined from four distances and three button widths. The button models are accurate representations of the shapes and sizes of the real buttons on the ETHD (see Section 3.3.3). The actual width measurement of each button (W) was then determined using the *Bounds* functionality in Unity, these four values of D and three values of W resulting in 12 values of ID (Equation 6.1) [115].

Table 8.3 presents the chosen range of 2.098-3.881 bits, which made the experience challenging while maintaining comfort. The higher end of the ID range is lower than

Table 8.3: Circle configurations for the Table Haptics Condition

<i>Diameter(mm)</i>	<i>D(mm)</i>	<i>W(mm)</i>	<i>ID(bits)</i>
170	167.4	25.1	2.939
170	167.4	36.7	2.475
170	167.4	51.0	2.098
230	226.5	25.1	3.325
230	226.5	36.7	2.842
230	226.5	51.0	2.444
290	285.6	25.1	3.630
290	285.6	36.7	3.135
290	285.6	51.0	2.722
350	344.7	25.1	3.881
350	344.7	36.7	3.377
350	344.7	51.0	2.956

that of the No Haptics Condition due to a number of physical limitations coming into play. The No Haptics Condition had no limits for the size of the completely virtual buttons and table size that could be configured. However, for the Table Haptics Condition, as it was also used as a control condition to the ETHD Haptics Condition, the reach of the ETHD affecting the range of D , while the physical size of the available buttons affected the size of W . A diameter of 350mm was deemed to be the maximum for the ETHD to accommodate the circle configurations of the three buttons chosen. For this experiment, circular buttons were required, and while four were available, one was nearing the 2cm width, the *fat finger problem* and the *occlusion problem* start to become a problem at this smaller size, the decision being taken to exclude this button, leaving three buttons available [116]. Since ID increases with an increase in D and a reduction in W , 3.881 bits was the maximum ID condition achievable given the above mentioned physical limitations.

The subjects were required to go through all 12 configurations per block, which were again presented sequentially in a randomised order, a single circle configuration being treated as one trial for this study, the circle again consisting of $n = 9$ buttons for nine movements per trial.

The practise round consisted of the user going through two conditions for a single block, the configurations being the largest value of D and the smallest and largest values of W . This exposed the subject to a total of 18 movements to become familiar

with before moving on to the main test. The decision to reduce the total number of practise round and main test movements arose from observing participants becoming fatigued and bored from going through too many monotonous movements in the No Haptics Condition. These two elements could contribute to users trying to finish the test as fast as possible without caring about accuracy. Therefore, by reducing the total number of movements to be done, the test could be completed in a shorter time (10-15 minutes instead of 25-30) before users grew physically and mentally tired of the repetitive nature of the test.

The full test employed a $3 \times 4 \times 3$ within-subjects design, the user being required to go through combinations of the four distances and the three button widths for a total of 12 conditions in a randomised sequence per block, which consisted of three of these blocks. The circles for the full test consisted of nine buttons from which nine movements per trial arose, which resulted in 324 total movements recorded per user.

8.3.4 Experimental Procedure

As for the VR Alien Shooter Game Experiment, Table Haptics Condition sub-experiment was conducted at a dedicated room within the Chamber of Mines building, which was well-lit by natural light and also had an LED spotlight to improve the ambient lighting, to optimise the lighting conditions for hand tracking. For this experiment, the *VR Test* application was first started up manually and the Oculus Quest controllers were used in the first calibration scene to align the virtual blue control panel height to the physical table height. The controllers were also used to rotate the virtual control panel so that it was facing the user correctly. Lastly, a manual evaluation of the responsiveness of the button clicks using the haptic feedback of the table in a test scene was done. If the buttons were not responsive enough, the height of the virtual control panel was adjusted by 5mm at a time upwards or downwards until the button clicks felt responsive. The headset was then passed to the subject and they were assisted with fitting it on comfortably. The subject was then notified to read all instructions, and after entering age, gender and dominant hand data, the practise round began, followed by the main test.

The average time spent within the application was 10 minutes, the fastest being 7 minutes and the slowest 14, while the initial setup time including explanations, signing of the consent forms, calibrating the virtual and physical heights and fitting of the Oculus Quest typically took approximately 5-10 minutes. On average, 15-20 minutes was needed per subject for the full experiment procedure.

Table 8.4: Metrics per ID before data cleaning for the Table Haptics Condition

i	$ID(bits)$	$D(mm)$	$W(mm)$	$ER(\%)$	$\overline{MT}(ms)$	$SD_x(mm)$
1	2.098	167.4	51.0	5.70	835	17
2	2.444	226.5	51.0	5.70	909	24
3	2.475	167.4	36.7	4.27	903	13
4	2.722	285.6	51.0	6.27	943	25
5	2.842	226.5	36.7	3.99	961	21
6	2.939	167.4	25.1	5.98	1025	19
7	2.956	344.7	51.0	6.27	1007	48
8	3.135	285.6	36.7	6.27	967	26
9	3.325	226.5	25.1	7.55	1112	25
10	3.377	344.7	36.7	6.70	1063	34
11	3.630	285.6	25.1	4.27	1084	17
12	3.881	344.7	25.1	7.83	1159	37

8.3.5 Participants

A total of 26 volunteers participated in the study, this being the minimum sample size required, as determined in Section 7.7. Five of the subjects were female, two were left-handed, their average participant age being 21.8 and ranged from 18 to 39.

8.3.6 Data Reduction

A total of 8424 movements were captured (26 subjects x 3 blocks x 12 trials x 9 movements per trial), after which the data cleaning process was then performed, as described in Section 7.10. Starting with 8424 recorded movements and 312 potential pairs of IDe and $\overline{MT}$ for each condition across all users, a final total of 6518 valid movements for 308 pairs of IDe and $\overline{MT}$ values remained for analysis.

8.3.7 Data Analysis

All calculations were done on a per user per condition basis after cleaning the data, and unlike the No Haptics Condition, an increase in ID for the Table Haptics Condition did not result in a very obvious increase in error rate ER and error in accuracy SD_x as seen in Table 8.2. Instead, the error rate ER was tightly bound

to the range of 3.99%-7.83%, while the error in accuracy SD_x was tightly bound to the range of 13mm-48mm (Table 8.4). However, average movement time $\overline{MT}$ did increase for increasing values of ID , and were mainly affected by the distance component D .

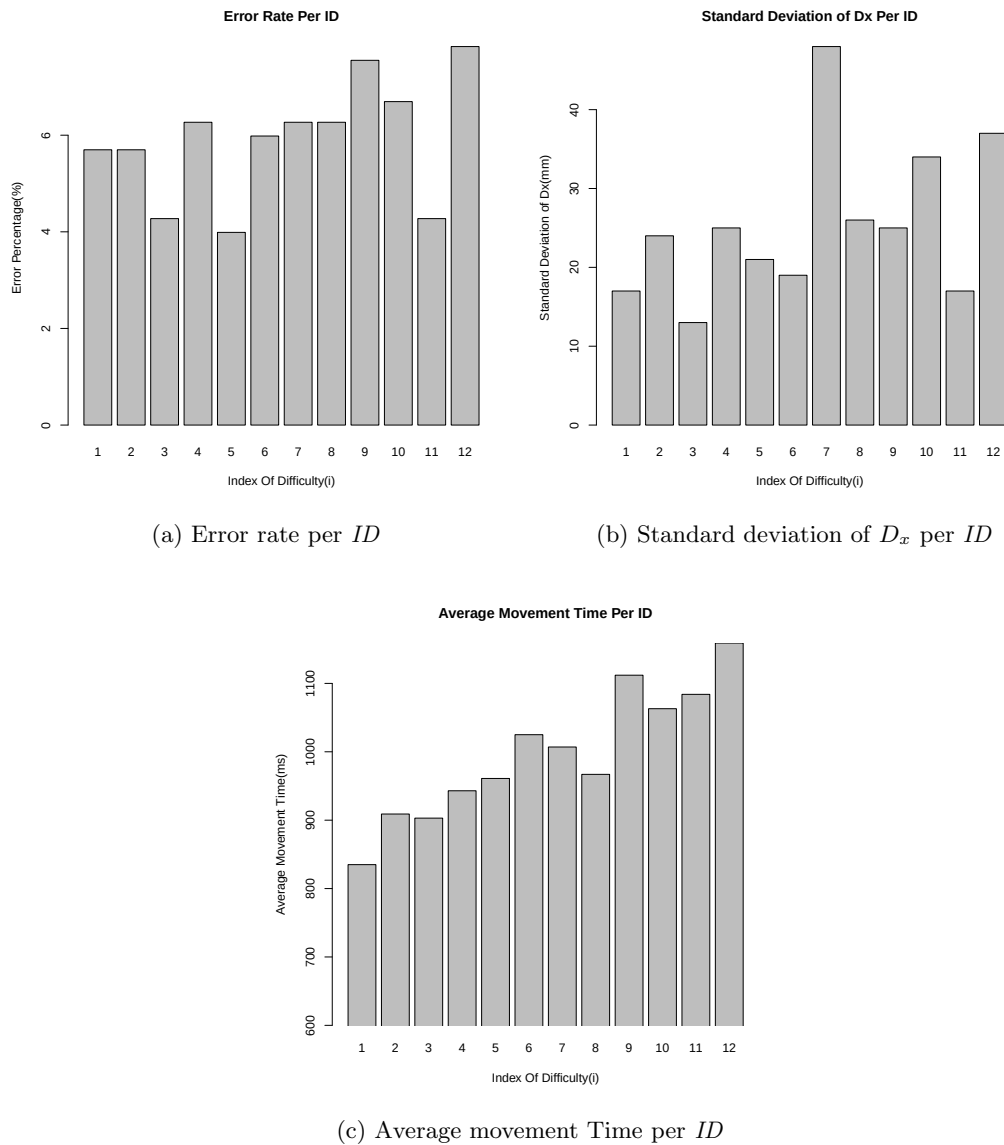


Figure 8.11: Average movement times, error rates and accuracy per ID for the Table Haptics Condition.

Figure 8.11a shows that there was a very slight increase in Error Rate overall as the ID increased, with $ID_{i=3}$, $ID_{i=5}$ and $ID_{i=11}$ dipping instead of following the trend. For the most part, the error rate ER was tightly bound to the range of 3.99%-7.83%, being noticeably smaller and less varied than that observed in Table 8.2 for the No

Haptics Condition. This could be attributed to the buttons being parallel to the table, which made it easier to view and target the centre of a button.

The error in accuracy SD_x was also observed to increase very slightly with increasing ID in Figure 8.11b, but as observed with the error rate, there were also dips for $ID_{i=3}$ and $ID_{i=11}$. A noticeable exception to this was for $ID_{i=7}$ which increased above all other values, and consisted of the largest distance and the button width, making it possible that users were ‘cheating’ by clicking on the edge of the button instead of aiming for the centre [112]. Again it was observed that these values of SD_x were much smaller than what was observed for the same ID values in Table 8.2 for the No Haptics Condition.

Unlike ER and SD_x , the average movement time $\overline{MT}$ did increase with increasing ID , as observed in Figure 8.11c. The values of $\overline{MT}$ for the Table Haptics Condition were on par with the same ID values in Table 8.2 for the No Haptics Condition.

8.3.8 Throughput Analysis

A least-squares linear regression was used to determine if there was a linear relationship between MT and ID , with the visual inspections of the Q-Q and density plots for the IDe and $\overline{MT}$ data in Figure 8.12 indicating that the data roughly followed a normal distribution. The Shapiro-Wilk normality test results for IDe , $W = 0.99017$ and $p\text{-value} = 0.03652$, indicate that the data does not follow a normal distribution, with $p\text{-value} < 0.05$ [119]. For $\overline{MT}$, the results were $W = 0.98923$ and $p\text{-value} = 0.02235$, indicating again that this data does not follow a normal distribution, the test for normality not passing.

In the Residuals vs Fitted plot in Figure 8.13, the blue line mainly follows the horizontal dashed grey line, but starts to move upwards towards the end, indicating that a mainly linear relationship between the predictor IDe and the outcome $\overline{MT}$ can be assumed. In the Scaled-Location plot in Figure 8.13, the blue line mainly follows a horizontal line pattern with equally spread out data points, which indicates that the data passes the homoscedasticity test. To confirm this, the Breusch-Pagan test gives the result of $BP = 0.094835$, $df = 1$, $p\text{-value} = 0.7581$ [124], the high $p\text{-value}$ above 0.05 and low BP test statistic confirming that the model did not violate the homoscedasticity assumption.

Due to the tests for normality failing, the non-parametric Kendall correlation test was used, the results being $\tau = 0.1953784$ and $p\text{-value} = 3.151 \times 10^{-7}$, with the

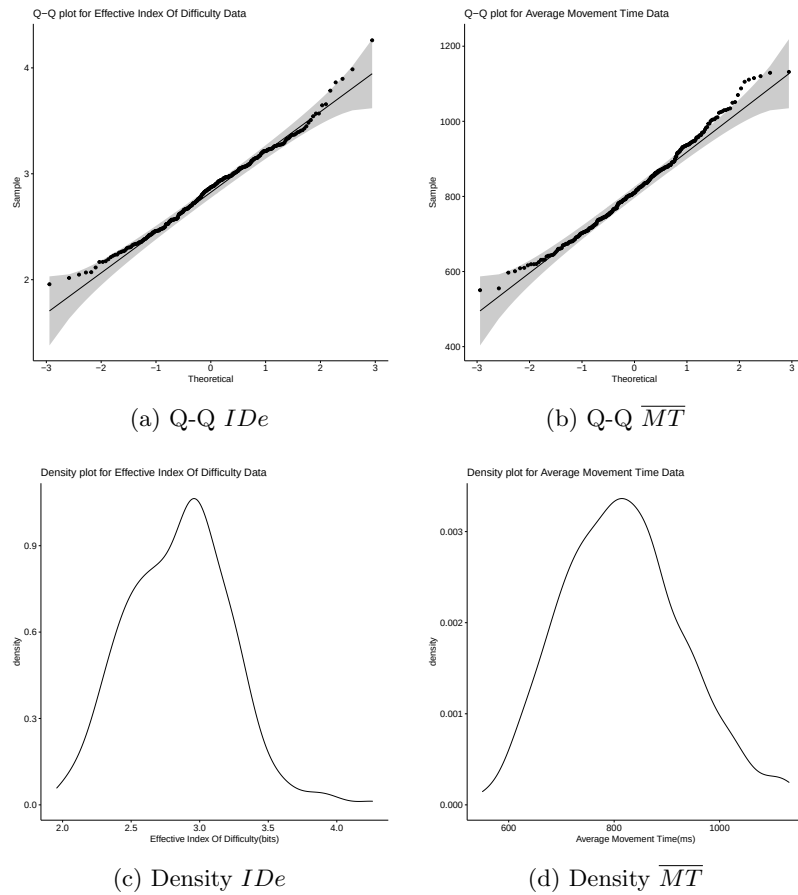


Figure 8.12: Q-Q and density plots for IDe and $\overline{MT}$ data for the Table Haptics Condition

p -value being less than the significance level of 0.05, indicating that IDe and $\overline{MT}$ were significantly correlated, and the correlation coefficient of 0.3544812 indicating a small effect size [123].

Again, it can be seen in Figure 8.14 that movement time increased with increasing ID after the data was cleaned, the intercept being at 551.8ms. For the Table Haptics Condition the practise round and main test was reduced to much fewer movements compared to the No Haptics Condition, which could have contributed to an increase in intercept. Due to the table providing haptic feedback, it was observed that users would get tired and some would feel sore from pushing their finger into the table. This could also have contributed to an increase in movement time if the users' fingers lingered for a very short while on the table after touching it.

While no cleaning of the trajectory data was performed, the lingering of the finger on the table could be regarded as dwell time that could be removed in future studies. As the user touches the table and quickly moves to the next target, it would be assumed

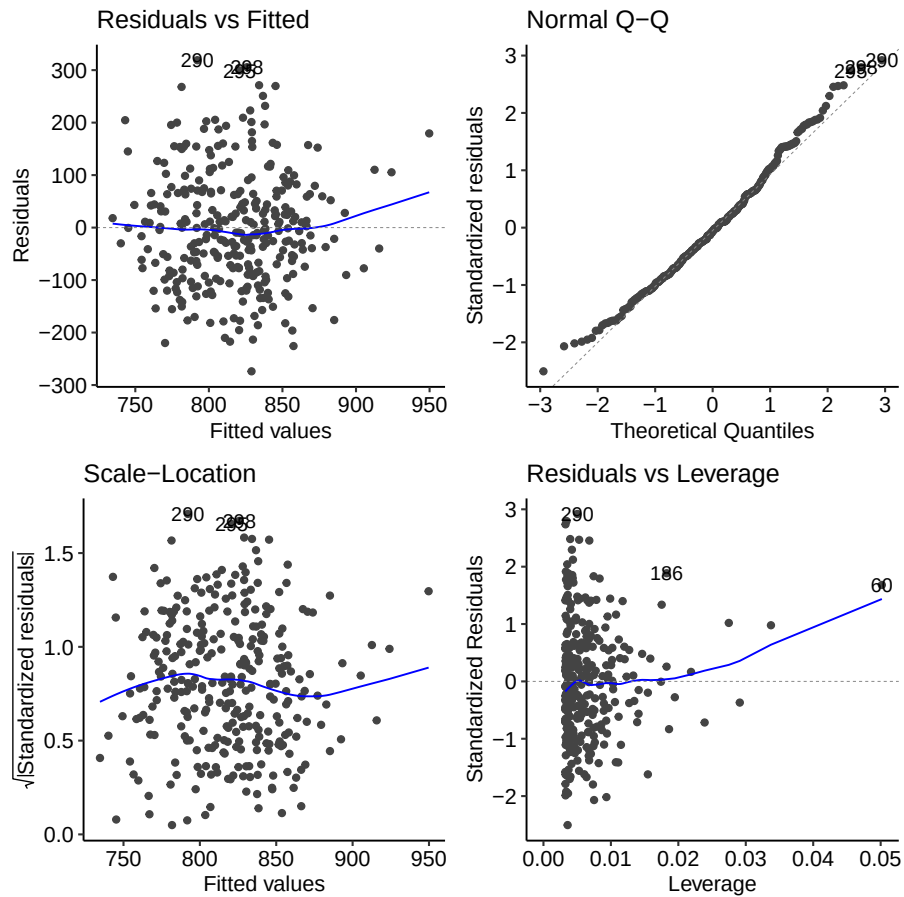


Figure 8.13: Plots on residuals for the Table Haptics Condition

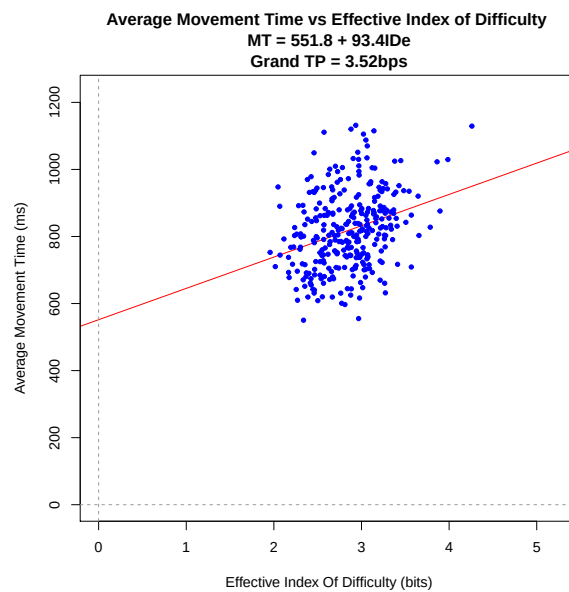
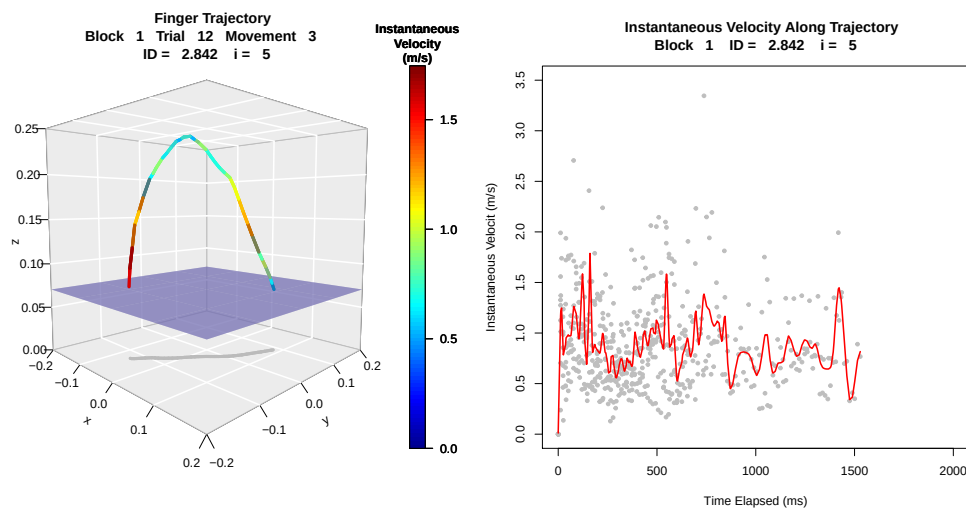


Figure 8.14: Average Movement Time vs Effective Index Of Difficulty IDe for the Table Haptics Condition

that as there was less movement than in the No Haptics Condition (Figure 8.8), and that the movement time would be slightly reduced. However, as seen in Table 8.4 and Table 8.2, average movement times remained consistent, this likely being due to the extra movement saved being negligible and offset by the user's finger lingering on the table.

Using the average of the effective Index of Difficulty values $\overline{IDe} = 2.848bits$, the standard error of the intercept was $361.17ms$, the large F-statistic and low p -value indicating that the regression model $MT = 551.8 + 93.4IDe$ was a statistically significant fit for the data ($F_{1,306} = 30.95$, $p\text{-value} = 5.795 \times 10^{-8}$). The minimum recorded throughput for a user was $2.59bps$ and the maximum $4.23bps$, the grand throughput for the Table Haptics Condition being $3.52bps$.

8.3.9 Movement Trajectory Analysis



(a) A typical finger trajectory for a single move- (b) The typical velocity profile for movement tra-
ment relative to the control panel plane jectories

Figure 8.15: An example of movement analysis for the Table Haptics Condition.

In the Table Haptics Condition it was confirmed that there was little to no extra movement after clicking on a target, considerably trimming down the total movement compared to the No Haptics Condition. As was the case for the No Haptics Condition, the velocity profile of a movement trajectory will never be stationary at the beginning and will start at a non-zero velocity, reduce as the user changes direction, and then accelerate towards the next target, slowing down again to click the target accurately (Figure 8.15a). The velocity profile observed was bound to a narrower range than

the No Haptics Condition, possibly due to users being able to change direction and move much more rapidly between targets due to the haptic feedback of the table. An example of this is depicted in Figure 8.15b, which was plotted from velocity data across all movements for a single trial for a subject. The total movement time was also bound to a narrower range than that observed for a similar *ID* value in the No Haptics Condition (Figure 8.7b) due to much more rapid movements.

8.4 ETHD Haptics Condition

The final sub-experiment (referred to as the ETHD Haptics Condition) focused on users performing the multidirectional tapping task with an ETHD, which provided dynamic passive haptic feedback and resulted from the interactions with the physical buttons attached to the ETHD. This experiment had the same circle configurations as the Table Haptics Condition, and entailed the subjects using their fingers to click the buttons on the ETHD (Figure 8.16). The physical sensation of clicking the button as well as the audible click sound effect indicated that the click had registered and that they could proceed to the next target. This type of haptic feedback is very realistic, but comes with the caveat that there is an inherent delay between button clicks when the ETHD moves to the next target. In this scenario, because the application knows where the next target is and the ETHD moves very quickly, the ETHD can immediately move to the next target position as soon as it is safe to do so, thereby reducing the delay to make the experience as responsive and realistic as possible.

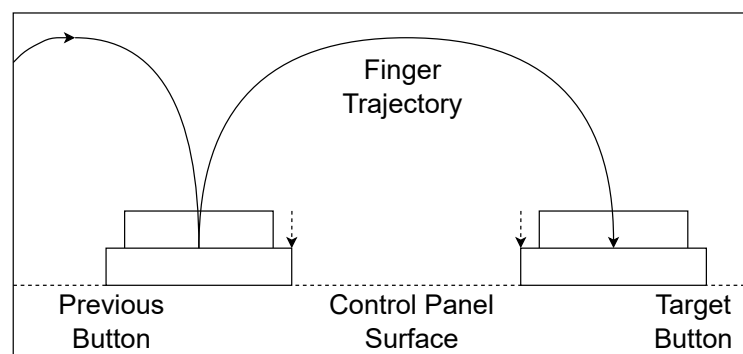


Figure 8.16: Finger trajectory over time with ETHD button haptics

8.4.1 Equipment

The *Fast ETHD* system was used for the ETHD Haptics Condition to provide realistic haptic feedback to the user with a small amount of delay (see Chapter 3). The Application Selected Target Control Scheme was used so that the ETHD moved to the next target as soon as it was safe to the user to do so (see Section 3.6.7). This was used for the experiment due to the requirement of the ISO/TS 9241-411 multidirectional tapping task for rapid movements from users. The targeted buttons were presented to the user in a pre-defined sequence so the application could already anticipate which target position to move to next in the sequence. The rig speed profile was set to maximum so that it could move between targets within the least amount of time possible. The rig was placed on top of a table, with a rubber sheet between it and the table providing enough friction to keep the position static and prevent it from jerking along the table due to the momentum generated when moving from target to target at high speed. The table was raised on bricks to reduce the angle between the user's head and the control panel on the rig, to allow for easier viewing of the control panel in the *VR Test* application and reduce how much users needed to bend their necks when viewing it.

The *QuestG2CoreBridge* application running on a laptop acted as a bridge between the Oculus Quest and the ETHD. The Oculus Quest's high-accuracy controllers are used for the initial calibration of the experiment so that the height and rotational positions for plane of the virtual blue table aligned to the physical height and rotational positions of the ETHD (see Section 3.6.2). The height of the interaction surface of the ETHD from the ground was 95cm.

8.4.2 User Interface

As was configured for the Table Haptics Condition, the control panel in the *VR Test* application is angled at 0° (parallel to the table) requiring users to look slightly downwards at the table (Figure 8.10), with the virtual button models being modelled to accurately match the size and shape of the real buttons that are attached to the ETHD (see Section 3.3.3). The real buttons on the ETHD provide realistic haptic feedback, and pushing a virtual button all the way until the user feels that the physical button cannot be pushed in further results in a click sound effect played to give the user audible feedback that the click has been registered by the software. The same 'scenes' for calibration of the virtual and physical height and rotational positions, inputs for dominant hand, gender and age choices, and the multidirectional tapping

task were used, with the user being given a practise round before the main Fitts's Test, both of which matched the configurations for the Table Haptics Condition, being two configurations for the practise round and twelve for the main test.

8.4.3 Experimental Design

Table 8.3 presents the chosen range of 2.098-3.881 bits across 12 circle configuration, which made the experience challenging while maintaining comfort. As discussed for the Table Haptics Condition, a diameter of 350mm was deemed to be the maximum for the ETHD to accommodate the circle configurations of the three buttons chosen, with 3.881 bits being the maximum ID condition achievable, given the above mentioned physical limitations when using the largest diameter and the smallest button width.

The subjects were required to go through all 12 configurations per block, these being presented sequentially in a randomised order with a single circle configuration being treated as one trial, consisting of $n = 9$ buttons for 9 movements per trial. The ETHD Haptics Condition sub-experiment used the same single block, two condition design for the practise round as the Table Haptics Condition for the largest value of D and the smallest and largest values of W , which exposed the subject to a total of 18 movements to become familiar with before moving on to the proper test. The full test employed a $3 \times 4 \times 3$ within-subjects design, with the user being required to go through combinations of the four distances and the three button widths for a total of 12 conditions in a randomised sequence per block, the user going through three of these blocks. The circles for the full test consist of nine buttons from which nine movements per trial will arise, which resulted in 324 total movements recorded per user.

8.4.4 Experimental Procedure

The experiment was conducted at the same dedicated room used for the Table Haptics Condition. For this experiment, the *VR Test* application was first started up manually and the Oculus Quest controllers were used in the first calibration scene to align the virtual blue control panel height, centre and rotational position to the physical ETHD height, centre and rotational position. A manual evaluation of the responsiveness of the button clicks using the haptic feedback of the ETHD in a test scene was then done. If the buttons were not responsive enough, an adjustment of the height of the virtual control panel was done 5mm at a time upwards or downwards

until the button clicks felt responsive. The headset was then passed onto the subject and they were assisted with fitting it on comfortably. The subject was then notified to read all instructions, and after entering their age, gender and dominant hand data, the practise round began, followed by the main test.

The average time spent within the application was 11.6 minutes, the fastest time being eight minutes and the slowest 16, with initial setup time including explanations, signing of consent forms, calibration of the virtual and physical orientations and fitting of the Oculus Quest typically taking 5-10 minutes. On average about 15-20 minutes was needed per subject for the full experiment procedure.

8.4.5 Participants

A total of 27 volunteers participated in the study, which was more than the minimum sample size of 26, as determined in Section 7.7. Ten of the subjects were female and one chose not to say, one was left-handed, and their average age was 26.4 years, ranging from 18 to 64.

8.4.6 Data Reduction

A total of 8748 movements were captured (27 subjects x 3 blocks x 12 trials x 9 movements per trial), with the data cleaning process being performed as described in Section 7.10. Starting with 8748 recorded movements and 324 potential pairs of IDe and $\overline{MT}$ for each condition across all users, a final total of 6194 valid movements for 306 pairs of IDe and $\overline{MT}$ values remained for analysis.

8.4.7 Data Analysis

All calculations were done on a per user per condition basis after cleaning the data. Unlike the Table Haptics Condition, an increase in ID for the ETHD Haptics Condition did result in a very obvious increase in error rate ER and error in accuracy SD_x as seen in Table 8.5. The error rate ER rose from of 13.17%-26.06% and the error in accuracy SD_x from 52mm-225mm. Average movement time $\overline{MT}$ also increased for increasing values of ID and were mostly affected by the distance component D .

Figure 8.17a shows that there was an easily observable increase in error rate overall as the ID increased, with $ID_{i=7}$ dipping instead of following the trend. The error

Table 8.5: Metrics per ID before data cleaning for the ETHD Haptics Condition

i	$ID(bits)$	$D(mm)$	$W(mm)$	$ER(\%)$	$\overline{MT}(ms)$	$SD_x(mm)$
1	2.098	167.4	51.0	13.17	1097	52
2	2.444	226.5	51.0	15.91	1093	74
3	2.475	167.4	36.7	20.03	1051	61
4	2.722	285.6	51.0	17.70	1111	94
5	2.842	226.5	36.7	19.62	1131	80
6	2.939	167.4	25.1	24.55	1193	62
7	2.956	344.7	51.0	16.05	1179	108
8	3.135	285.6	36.7	20.58	1175	99
9	3.325	226.5	25.1	25.51	1243	89
10	3.377	344.7	36.7	22.22	1207	121
11	3.630	285.6	25.1	26.06	1242	102
12	3.881	344.7	25.1	26.06	1261	225

rate ER was in the range of 13.77%-26.06%, these being higher than that observed for the Table Haptics Condition (Table 8.4), and slightly higher than for the No Haptics Condition (Table 8.2). This could be attributed to the more realistic haptic feedback from real buttons and the dynamic nature of the ETHD moving between targets.

The error in accuracy SD_x was also observed to increase with increasing ID in Figure 8.17b. A noticeable exception to this is for $ID_{i=12}$, which increases above all other values instead, this corresponding to the same ID range for the No Haptics Condition in Table 8.2. At higher ID values, higher SD_x values are observed due to more misses, with extreme misses being caused by double click errors, which can cause the SD_x value to become close to the D value for that trial, as observed in Table 8.5.

Average movement time $\overline{MT}$ also increased with increasing ID , as observed in Figure 8.17c, the average movement times recorded for the ETHD Haptics Condition being slightly higher than what was observed for the No Haptics Condition. For $ID_{i=12}$ in the ETHD Haptics Condition, $\overline{MT} = 1174ms$, which was around the same $\overline{MT}$ of 1254ms for $ID_{i=16}$ of the No Haptics Condition and $\overline{MT} = 1159ms$ for $ID_{i=12}$ of the Table Haptics Condition. There was an inherent delay that added to the movement time when using the ETHD due to it moving from target to target. Despite there being an added amount of movement time at the lower ID values, this

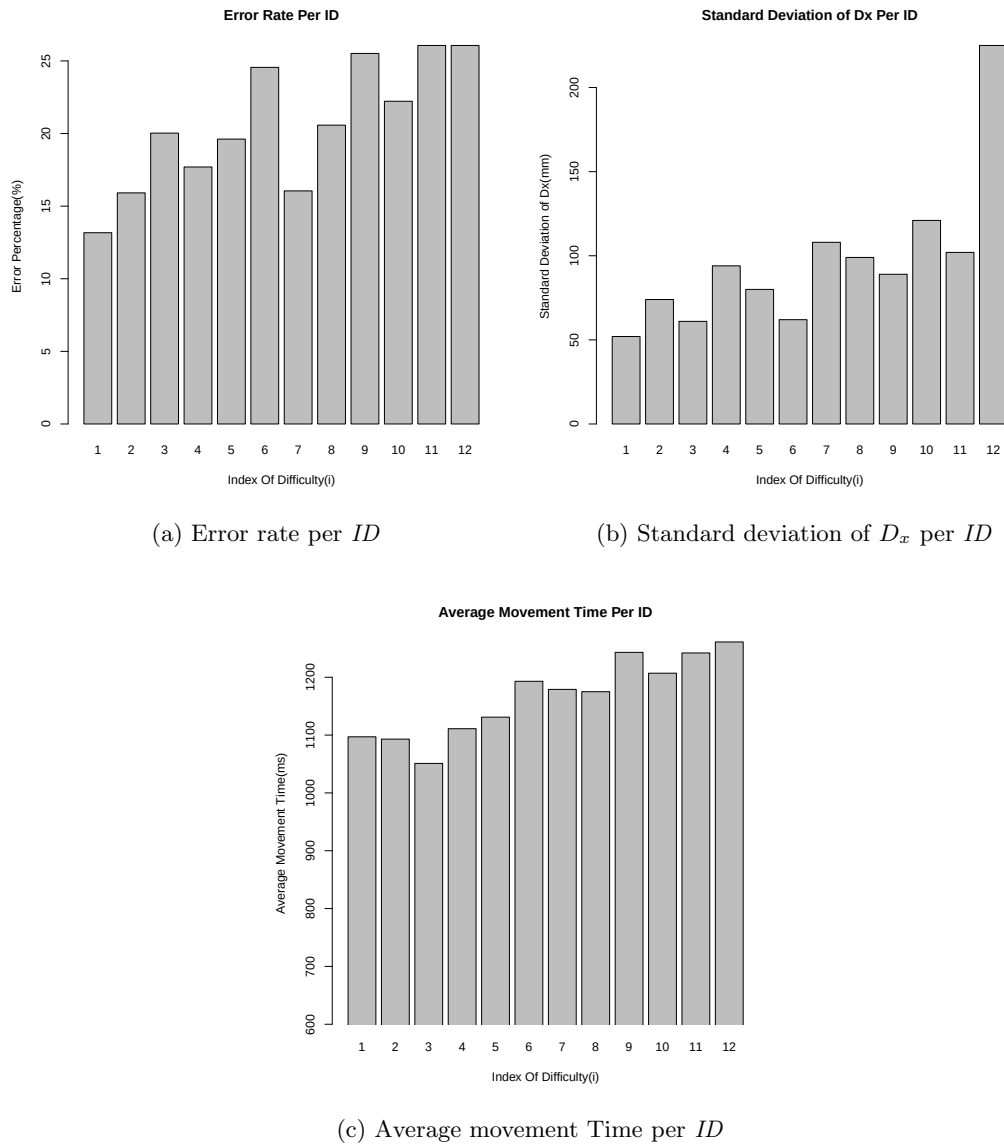


Figure 8.17: Average movement times, error rates and accuracy per ID for the ETHD Haptics Condition.

was very similar at higher ID values, which implies that the ETHD was moving fast enough to keep up with user movements similar to zero-delay conditions like the Table Haptics and No Haptics Conditions.

8.4.8 Throughput Analysis

A least-squares linear regression was used to determine if there was a linear relationship between MT and ID , with the Q-Q and density plots for the IDe and

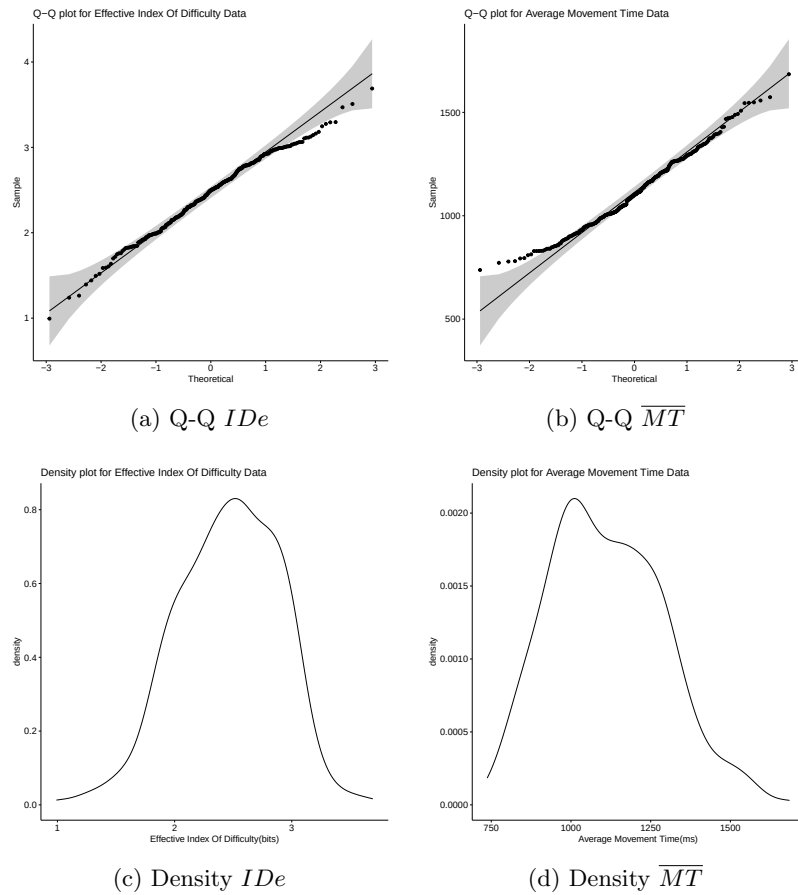


Figure 8.18: Q-Q and density plots for IDE and $\overline{MT}$ data for the ETHD Haptics Condition

$\overline{MT}$ data in Figure 8.18 indicating that the data roughly followed a normal distribution. The Shapiro-Wilk normality test results for IDE gave $W = 0.99106$ and $p\text{-value} = 0.05989$, indicating that the data follows a normal distribution, as $p\text{-value} > 0.05$ [119]. For $\overline{MT}$, the results were $W = 0.98495$ and $p\text{-value} = 0.002725$, indicating that this data did not follow a normal distribution, meaning that the test for normality did not pass.

In the Residuals vs Fitted plot in Figure 8.19, the blue line does not follow the horizontal dashed grey line but curves around it, with a linear relationship between the predictor IDE and the outcome $\overline{MT}$ not being assumed. In the Scaled-Location plot in Figure 8.19, the blue line can be observed to mainly follow a horizontal line pattern with equally spread out data points which indicates that the data passes the homoscedasticity test. To confirm this, the Breusch-Pagan test gives the result of $BP = 2.1378$, $df = 1$, $p\text{-value} = 0.1437$, with a high $p\text{-value}$ above 0.05 and a low BP test statistic confirming that the model does not violate the homoscedasticity

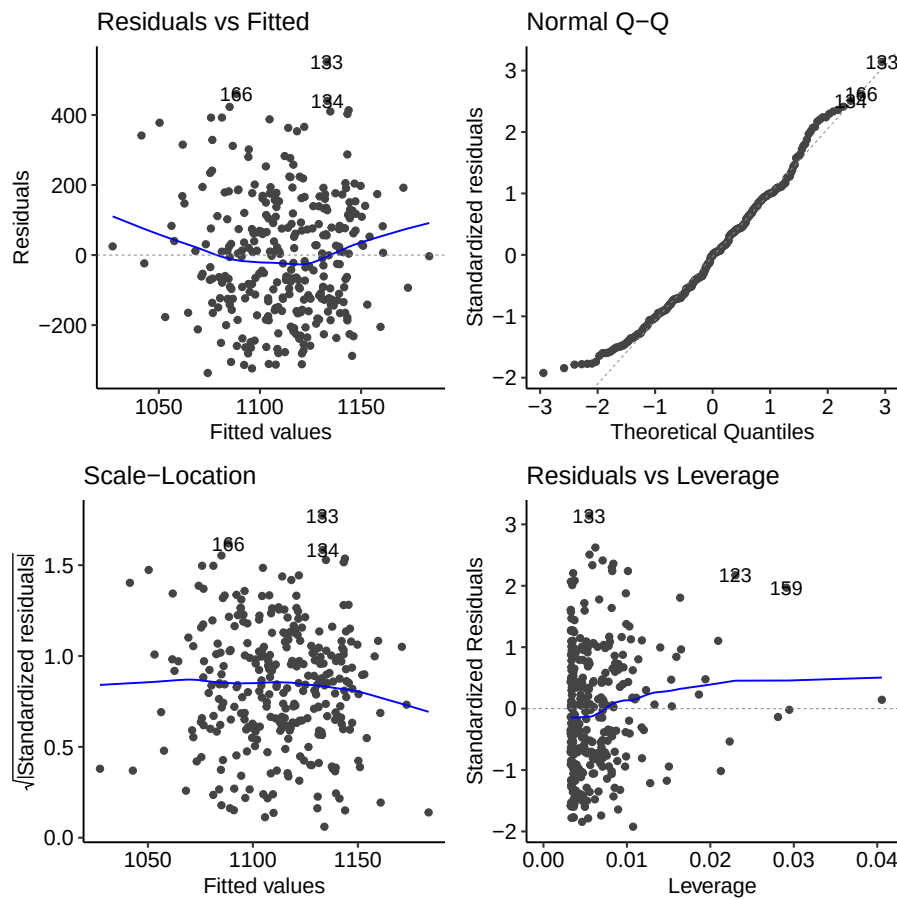


Figure 8.19: Plots on residuals for the ETHD Haptics Condition

assumption [124].

Due to the tests for normality and linearity failing, the non-parametric Kendall correlation test was used [123], the results being $\tau = 0.1102539$ and $p\text{-value} = 0.004021$, the latter being less than the significance level of 0.05. Therefore, it can be concluded that IDe and $\overline{MT}$ are significantly correlated, the correlation coefficient of 0.1102539 indicating a small effect size.

It can be seen in Figure 8.20 that movement time increased with increasing ID after the data was cleaned, with the intercept being at 969.5ms. This intercept was almost double the No Haptics (522.1ms difference) and Table Haptics (417.7ms difference) Conditions, and can be attributed to the inherent delay in the ETHD system when changing target positions. This latency arose from the time the *VR Test* application sends a new target position over WiFi to the *QuestG2CoreBridge* application, processing and g2core format conversion of the new position, processing on the Arduino Due microcontroller board, and the g2core firmware sending the necessary signals to the stepper motors to move until the desired position is reached.

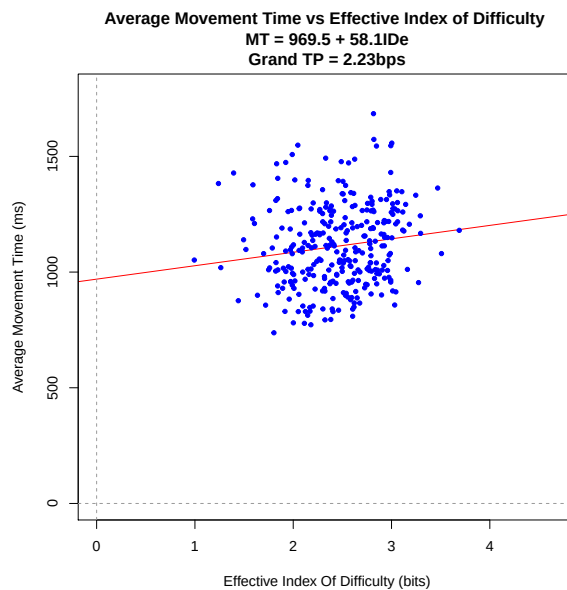


Figure 8.20: Average Movement Time vs Effective Index Of Difficulty IDe for the ETHD Haptics Condition

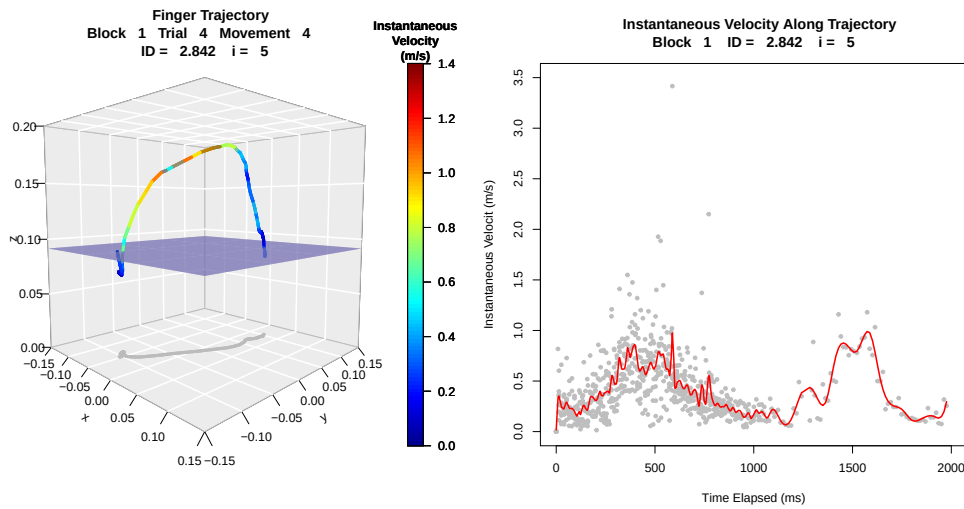
All these steps contributed to a large chunk of the difference in intercept (417.7-522.1ms).

No cleaning of the trajectory data was being performed, the lingering of the finger on the ETHD buttons potentially being regarded as dwell time that could be removed in future studies. However, due to the spring-like nature of the buttons, it is assumed that the users did not spend too much time in contact with them and that this ‘lingering’ time can be regarded as negligible.

Using the average of the effective Index of Difficulty values $\overline{IDe} = 2.46bits$, the standard error of the intercept was 366.91ms, the large F-statistic and low p -value indicating that the regression model $MT = 969.5ms + 58.1IDe$ was a statistically significant fit for the data ($F_{1,304} = 6.275$, $p\text{-value} = 0.01277$). The minimum recorded throughput for a user was 1.26bps and the maximum 2.96bps, the grand throughput for the ETHD Haptics Condition being 2.23bps.

8.4.9 Movement Trajectory Analysis

In the ETHD Haptics Condition it was noted that there was a little extra movement after clicking a target, due to the user pushing their finger into and away from the physical button. As was the case for the No Haptics and Table Conditions, the



(a) A typical finger trajectory for a single movement relative to the control panel plane (b) The typical velocity profile for movement trajectories

Figure 8.21: An example of movement analysis for the ETHD Haptics Condition.

velocity profile of a movement trajectory will never be stationary at the beginning and will start at a non-zero velocity and reduce as the user changes direction. However, after changing direction towards the new target, instead of accelerating towards it, the user clicks the target in a much slower way than what was observed for the No Haptics and Table Haptics Conditions (Figure 8.21a). This is due to their waiting for the *Safety Height* to indicate that it is safe to click the target button, the latency introduced by the ETHD and *Safety Height* indicator slowing down the users' movements. The velocity profile observed being bound to an even narrower range than the Table Haptics Condition due to the latency introduced and users being more careful when clicking the target buttons. An example of this is depicted in Figure 8.21b, which was plotted from velocity data across all movements for a single trial for a subject. The total movement time range is comparable to that observed for a similar *ID* value in the No Haptics Condition (Figure 8.7b). There are some exceptions where users wait longer than necessary to click the button, which is why there are fewer data points beyond the 1200ms mark. The maximum range of 2000ms is still acceptable, given that participants were still novices. If more training to anticipate the ETHD movements was given, it is assumed that the movement time range would narrow down to more closely match the Table Haptics Condition range.

Table 8.6: Mean and standard deviation results for No Haptics, Table Haptics and ETHD Haptics Conditions

Condition	Mean(bps)	Standard Deviation(bps)
No Haptics	3.70	0.476
Table Haptics	3.53	0.436
ETHD Haptics	2.23	0.386

8.5 Inter Experiment Comparison

After all three experiments were analysed individually, the results were compared between the No Haptics, Table Haptics and ETHD Haptics Conditions. This section will discuss how error rates, accuracy, movement time and grand throughput outcomes compare across the three conditions, as well as the results from two different formal comparisons for the throughput values.

A direct comparison in the form of an independent samples t-test on the throughput values between the Table Haptics and ETHD Haptics Conditions was done, the only difference between them being the method of haptic feedback used, which resulted in threats to validity being quite low.

As there are three conditions to consider when factoring in the No Haptics Condition, it would also be interesting to perform a One-Way ANOVA test on the throughput values across all three haptics conditions. However, the No Haptics Condition was performed with many different changes in the experiment methodology, since it was initially used as a pilot study to test out the *VR Test* application. In this experiment, varying height positions, lighting conditions, an angled virtual control panel, a large range of ID values and increase in movements overall contributed to threats to validity. Therefore, this must be kept in mind when interpreting the results of the One-Way ANOVA test across all three conditions.

8.5.1 Differences in experimental results

Table 8.6 summarises the average throughput and standard deviations of the three haptic conditions, and while previous studies have shown that adding haptics yields better throughput than without it, in this case the superior throughput from the No Haptics Condition is most likely attributed to the virtual control panel being

angled at 45° and the height adjusted to be most comfortable for the user. Given this positioning, the user would be able to click on the buttons in a much easier fashion, as the actuator of the button is more easily in line with the user's vision and to click it directly with a forward motion click. For the Table and ETHD Haptics Conditions, the virtual control panel was parallel with the table and the height was static. Therefore, users would have varying degrees of perspective and reach to click the button. To align the finger of a first-time VR user with the actuator of the button takes significantly more effort for these conditions compared to the No Haptics Condition. The No Haptics Condition had a longer practice round as well as more conditions in general, which could have improved the results by enabling participants to become more accustomed to the test. However, the No Haptics Condition was more prone to users finding it monotonous and fatiguing due to an almost 66% increase in the total number of movements across the practice and main test rounds, and did not need to have a pause as they did when they touched the table. In the No Haptics Condition, the user could immediately move their hand to the next target as soon as they heard the click, unlike the Table and ETHD Haptics Conditions, where the aim was to touch the haptics surface.

8.5.2 Difference in means for Table Haptics and ETHD Haptics Conditions

To test if the means of the Table Haptics and ETHD Conditions are significantly different, it first needs to be determined if the parametric unpaired two-samples t-test could be used or the non-parametric two-samples Wilcoxon rank test. For the unpaired two-samples t-test, the data had to be checked to establish if they were independent, followed a normal distribution and had the same variance. The samples were independent as they differ in haptic feedback method. For the check for normality, Q-Q and density plots in Figure 8.22 visually confirmed that the throughput data for each experiment followed a normal distribution. This was verified using the Shapiro-Wilk normality test, with a p -value > 0.05 confirming a normal distribution for the data [119]. For the Table Haptics Condition $W = 0.97028$ and p -value = 0.6306 and for the ETHD Haptics Condition $W = 0.97502$ and p -value = 0.737, indicating that the throughput data for both conditions were normally distributed.

An F-test was then done to check if the throughput data for both conditions had equal variance (homoscedasticity), the results being $F = 0.78404$ and p -value = 0.5415. The p -value was greater than the significance level of 0.05, indicating that there

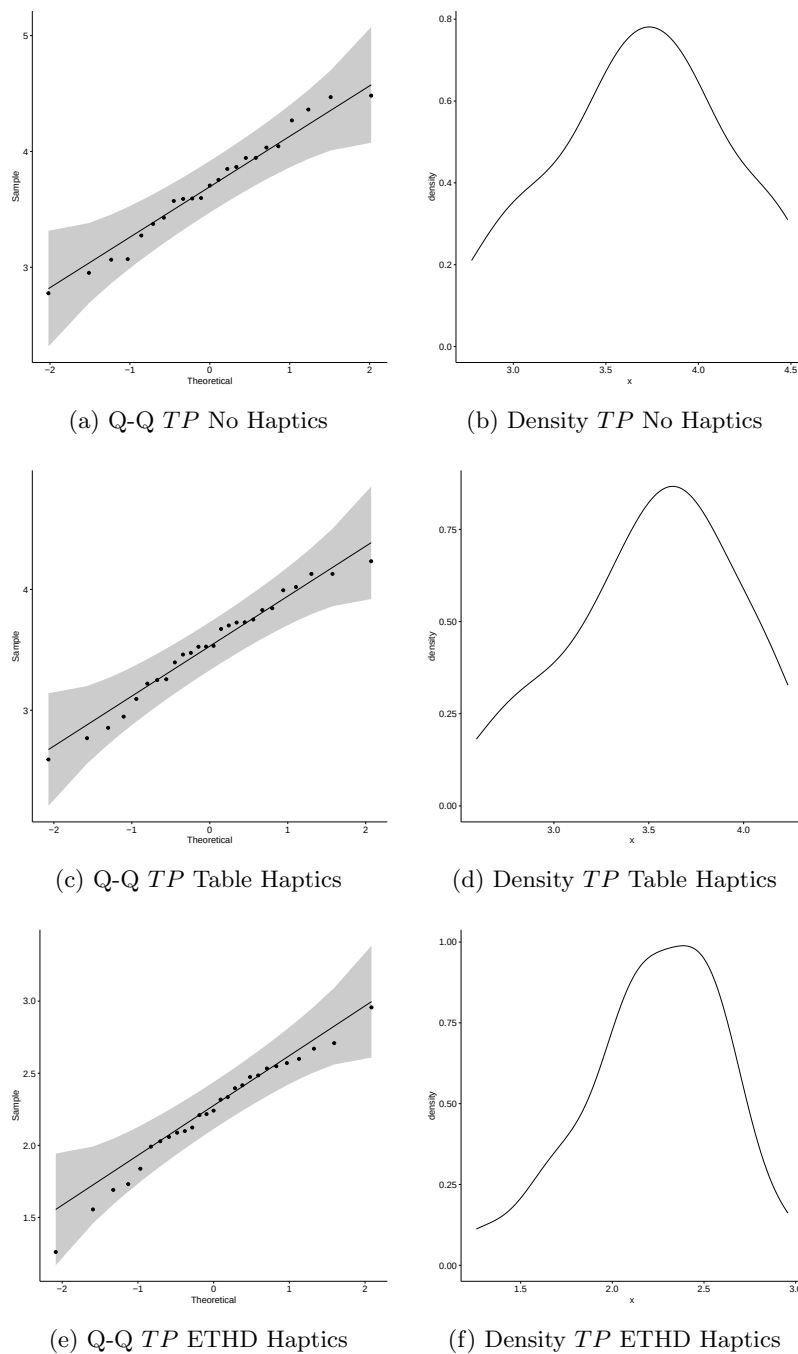


Figure 8.22: Q-Q and density plots for throughput TP across all conditions

was no significant difference between the variances of both sets of data.

The parametric unpaired two-samples t-test could therefore be used to check if the throughput means differ significantly, the results from the test being $t = -11.489$ and $p\text{-value} = 9.211 \times 10^{-16}$ [119]. As the $p\text{-value}$ is less than the significance level of 0.05, the throughput means for the Table Haptics and ETHD Haptics conditions were regarded as being significantly different, as indicated in Figure 8.23.

Using Cohen's d , the effect size was determined to be 3.15, indicating a large effect, with an optimal ETHD design ideally yielding an insignificant to small effect. This indicates that the ETHD design still needs significant improvements until it can come close to the performance of a zero-latency haptic feedback method, with many methods being available to improve the latency of ETHD systems in future designs. A reduction in latency could potentially come from the use of faster wireless communication methods such as WiFi 6, the latest evolution of Bluetooth or a completely new method. The Arduino Due runs at 84 MHz with only 96kb of SRAM, with a faster microprocessor with more memory combined with a more optimised version of the g2core firmware, or a completely different firmware that is more optimised, being used to reduce latency. This first version of the Quest has a hand tracking rate of 30Hz, which is much lower than that of the Leap Motion Controller that operates at 120Hz for hand tracking [93,96]. Occasional tracking issues occur for certain hand orientations, with improvements in hand tracking capability and sampling rate also contributing to closing the gap in throughput for ETHD and zero-latency haptics.

8.5.3 Difference in means for No Haptics, Table Haptics and ETHD Haptics Conditions

Many studies with VR and Fitts's Law have showed that adding haptic feedback usually results in an increase in throughput [29,31]. As mentioned previously, the No Haptics Condition experiment was not as controlled as the Table Haptics and ETHD Haptics Conditions, with time constraints preventing the experiment being redone in a more controlled manner to match the Table Haptics and ETHD Haptics Conditions. However, to this author's knowledge at the time of writing, it was the first experiment conducted to determine the throughput of the Quest's hand tracking capabilities, with data collected being useful for comparisons with the other haptic feedback conditions. Keeping in mind that the variations of the No Haptics Condition must be considered as threats to validity, the comparisons can still be

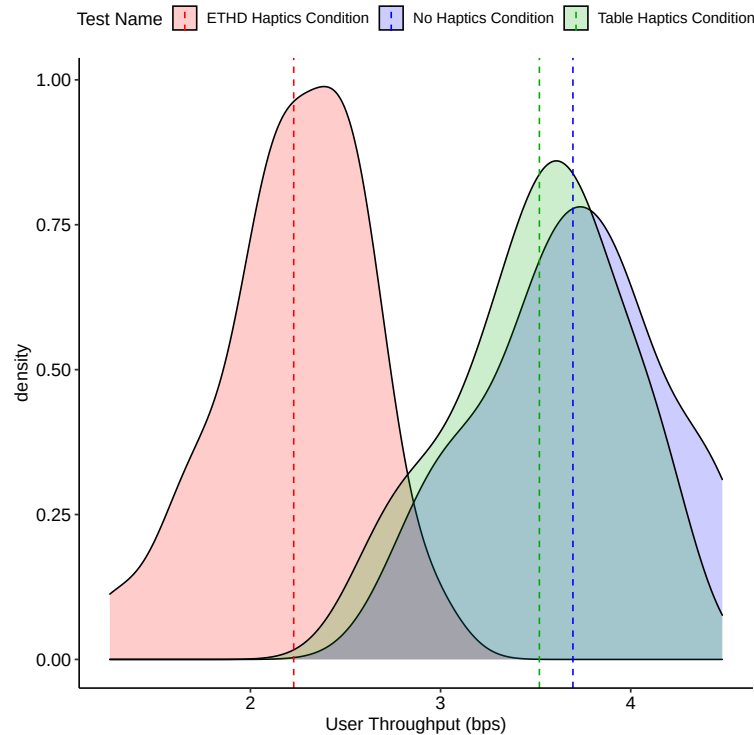


Figure 8.23: Density plots for throughput TP across all conditions

done and explained. As there are three sets of throughput data for the No Haptics, Table Haptics and ETHD Haptics Conditions, the ideal tool to use for analysis was the parametric One-Way Analysis of Variance (ANOVA) test, which requires assumptions of independent samples, normal distributions of all sets of data, and that they should have the same variance. If any of these assumptions are not met, the non-parametric Kruskal-Wallis rank sum test can be used.

The data was sampled independently from three different sub-experiments with the single factor of the haptic feedback method changing. The throughput data from the Table Haptics and ETHD Haptics Conditions were already verified to follow normal distributions. Using the Shapiro-Wilk normality test on the No Haptics Condition throughput data, the resultant test statistics were $W = 0.97401$ and $p\text{-value} = 0.7838$, the $p\text{-value}$ being above the significance level of 0.05, indicating that the data is normally distributed, as indicated in Figure 8.22 [121]. Levene's Test was used to check for homogeneity of variance across the data sets, a test result of $F = 0.5846$ and $p\text{-value} = 0.5599$ indicating that the variances were not significantly different across the data sets for No Haptics, Table Haptics and ETHD Haptics Conditions.

With the three assumptions verified, the One-Way ANOVA test was confidently used,

Table 8.7: Multiple pairwise-comparison results from Tukey’s Honest Significant Differences test for No Haptics, Table Haptics and ETHD Haptics Conditions throughput data

Test Pair	Difference(bps)	p -value	Cohen’s d	Effect Size
Table - ETHD	1.298	< 0.001	3.15	Large
No Haptics - ETHD	1.469	< 0.001	3.39	Large
No Haptics - Table	0.171	0.355	0.375	Small

a test result of $F = 89.6$ and $p\text{-value} < 2 \times 10^{-16}$ indicating that the throughput means across the No Haptics, Table Haptics and ETHD Haptics Conditions were significantly different [121]. This implies that each haptic feedback method had a significant effect on the throughput of the user, as indicated in Figure 8.23.

Tukey’s honest significant differences test was then used for multiple pairwise-comparison between the means of the data sets, and Cohen’s d was used to determine the effect size between the pairs (Table 8.7). The effect size for the ETHD Haptics Condition compared to the other two were large, this being expected, as the inherent delay from the ETHD system introduced more movement time and thus lowered the throughput. Despite this effect size being large, it equates to a throughput difference of 1.298-1.469bps, and in terms of the larger comparison to other device setups (see Table 8.8 and Figure 8.24), this gap is not too large and could be made smaller in future ETHD designs based on the recommendations given earlier. The effect size between the No Haptics and Table Haptics Conditions is small, with a difference of just 0.171bps, which was expected, as both are zero-latency conditions. However, what is unexpected is that the Table Haptics Condition throughput mean is lower than that of the No Haptics Condition, which goes against what previous studies observed [29, 31]. This could be attributed to the fact that each user was able to adjust the vertical position of the test to their own height for optimal comfort and reach, as the test faced them directly, requiring no bending of the neck. The virtual control panel was also angled towards the participant to allow them to click the buttons much more easily than the Table Haptics and ETHD Haptics Conditions, where the control panel was parallel to the table.

Table 8.8: Throughput per device setup

Device Setup	Throughput (bps)
Touchscreen (Upper)	6.85
Touchscreen (Lower)	6
Mouse (Upper)	4.9
Oculus Rift Development Kit 2 + Leap Motion + Haptic Feedback	4.7
Oculus Rift Development Kit 2 + Leap Motion	4.1
HTC Vive Pro Eye + Controller	4
Oculus Quest (No Haptics)	3.7
Mouse (Lower)	3.7
Oculus Quest (Table Haptics)	3.52
HTC Vive Pro Eye + Leap Motion	3.5
Touchpad (Upper)	2.9
CAVE + Stylus + Haptic feedback	2.56
Isometric Joystick (Upper)	2.55
CAVE + Stylus	2.37
Oculus Quest (ETHD Haptics)	2.23
Kinect 2D	2.1
Leap Motion + Laptop Screen + Wireless Presentation Clicker	1.9
Isometric Joystick (Lower)	1.6
Kinect 3D	1.06
Touchpad (Lower)	0.99

8.5.4 Comparisons to previous studies

Fitts's Law is important to consider when designing user interfaces, whether it be physical control panels and devices, operating systems, websites or VR interfaces. Designing an interface to have low ID values between components will make working on it easier, more useful and user-friendly, with studies such as this one offering a wealth of information to consider when designing these interfaces.

Ultimately, the goal of a Fitts's Law test is to determine the throughput of a device setup, with Table 8.8 and Figure 8.24 summarising the throughput arising from the conditions observed in this study and previous studies. The experiments with

the Oculus Quest from this study determined a grand throughput of 3.7bps for the No Haptics Condition, 3.52bps for the Table Haptics Condition and 2.23bps for the ETHD Haptics Condition. The throughput for the No Haptics and Table Haptics Condition is on par with the lower end of the throughput range for the mouse (3.7-4.9bps), while for the ETHD Haptics Condition, it is on par with the upper end of the throughput range for the isometric joystick (1.6-2.55bps) and the Kinect (1.06-2.1bps).

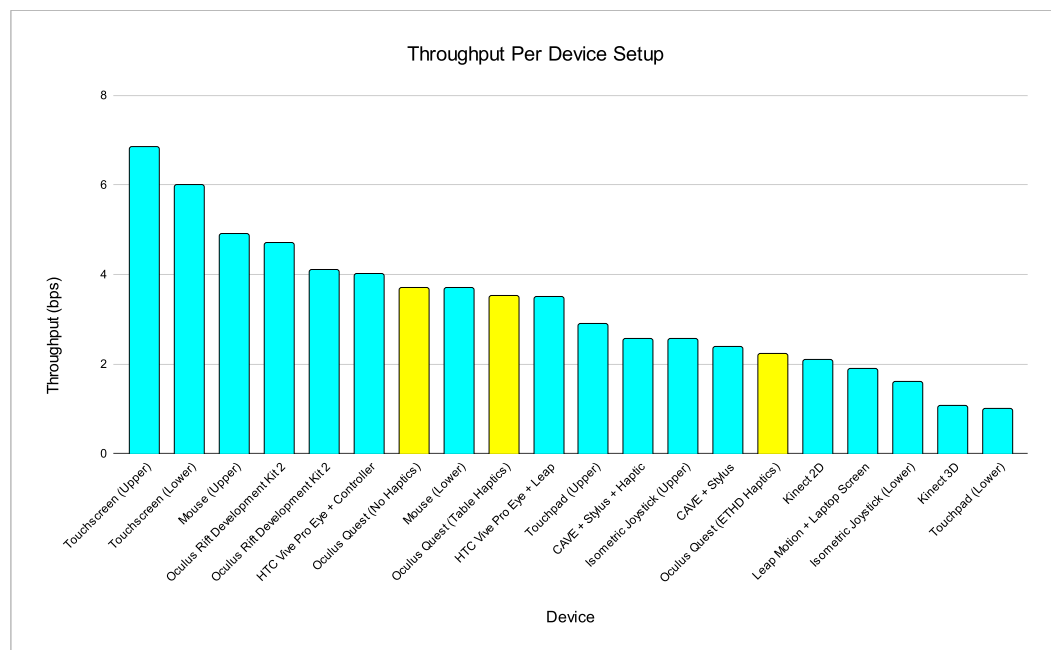


Figure 8.24: Throughput per device setup

The 2D and 3D experiments with the Microsoft Kinect by Pino *et al.* yielded a throughput of 2.1bps and 1.06bps respectively [113]. Teather *et al.* determined 2.37bps without haptic feedback and 2.56bps with haptic feedback for a stylus in a CAVE setup [29]. Joyce and Robinson determined 4.1bps without haptic feedback and 4.7bps with haptic feedback using the Leap Motion Controller for hand tracking with the Oculus Rift Development Kit 2 [31]. Mutasim *et al.* determined a throughput of around 4bps using the Vive controller with the HTC Vive Pro Eye for clicking on targets and around 3.5bps with the Leap Motion Controller enabling a pinching action to select targets [114]. MacKenzie determined 6.85bps for a touchscreen [111], while Burno *et al.* determined around 6bps for a touchscreen and 2bps for hand tracking using the Leap Motion Controller [110]. Touchscreens appear to yield the best throughput due to the direct input from the user instead of indirect input, such as through the mouse pointer and click [111].

The throughput determined from the No Haptics and Table Haptics Conditions of this study is comparable to the lower end for the mouse, the no haptics condition in Joyce and Robinson's study, and the values for clicking and pinching by Mutasim *et al.* It is much higher than the throughput values yielded from the studies by Pino *et al.*, a throughput of 3.7bps indicating that the Oculus Quest's hand tracking capabilities are quite capable of providing the user with precise and responsive control. In addition, the fact that the Oculus Quest requires no extra hardware for hand tracking makes it an even more appealing device. Unlike some previous studies, it was observed that the Table Haptics Condition yields a slightly smaller throughput than the expected increase, this being explained as the No Haptics Condition having much more variation, which could have contributed to this result. It may be worth repeating the No Haptics Condition with the Oculus Quest in future studies with the same experiment setting as the Table Haptics Condition to establish if the results remain the same or show an increase in throughput. The ETHD Haptics Condition is on the lower end of the list, this being due to the inherent delay in the ETHD setup. As discussed previously, improvements to the ETHD design could be used to increase throughput, possibly coming close to the levels of zero-latency conditions. Even with the current levels of latency, ETHDs perform better than the Kinect and isometric joysticks and touchpads in some instances. Of note for this study and the throughput determined is that:

- The physical distances between targets was much larger than most other studies in the range of 167-600mm, and much larger than the distances needed for moving a mouse on a screen (pixels versus millimetres), thereby contributing to larger movement times and reduced throughput (Equation 6.3).
- The subjects were not given the opportunity to reach expert levels prior to these tests and were tested as novices, having been given the bare minimum practise time to get used to the interface and test proceedings. It might be worth conducting these tests with expert level users to determine if that increases throughput.
- Most Fitts's Law tests require users to travel in a straight line to targets, while these tests required them to move more naturally, resulting in arc movements. The 2D point-to-point distance was used rather than the full 3D trajectory distance, the latter possibly yielding a larger *ID* range and thereby contributing to a better throughput (Equation 6.1). However, using the full 3D trajectory distance might require some modifications of Fitts's Law to accommodate 3D movements.

- The hand tracking feature of the Oculus Quest is relatively new, having first been added to the platform towards the end of 2019. Improvements in the software and neural network used to provide this feature would surely improve throughput over time.

It must be noted that using hand tracking on the Oculus Quest did not come without its shortcomings, there were occasional hand tracking issues, being caused by either lighting conditions or hands occluding each other, which could be improved by using better cameras, image processing or more training of the neural networks. As of April 2022, Meta has introduced the Hand Tracking 2.0 update to the Meta Quest 2 (previously known as the Oculus Quest 2), which has vast improvements over the hand tracking version in this study [125]. Fatigue may also have been an issue, with a user interacting with a VR interface in mid-air being very likely to become tired, as was observed during the No Haptics Condition. A questionnaire provided by ISO/TS 9241-411 evaluates user fatigue, which could be used in future studies to gain more insight on this issue. It was observed that the inclusion of haptics in the Table Haptics and ETHD Haptics Conditions did ease the fatigue experienced by users, with another potential solution being for VR interface designers to incorporate breaks (such as in this study) or workflows that reduce fatigue.

It was noted that the upper end of the ID range for this study was limited to 3.881-4.808bits, despite the recommendation for a range of 2-8bits [112], which would be easier to implement when the pointing device is more precise. A mouse pointer tip is a single pixel, which makes smaller targets feasible, compared to a fingertip, which is in the order of millimetres. In the case of VR with hand tracking, as in this study, button widths smaller than 2cm could increase the ID range but severely impact user experience due to the *fat finger problem* and the *occlusion problem* [116]. It can be observed from Table 8.2 and Figure 8.3a that the circle configurations with the smallest button width yielded the most errors, which is an indication that these scales are not suitable for the context of hand tracking in VR. It might be possible to increase this ID range in future studies by changing the virtual representation of the hand to something more precise such as a skeleton hand made out of fine lines. It might also be worth conducting the same test with one of the Oculus Touch controllers for comparison, as this was effectively used as a mouse for this platform.

8.6 Conclusions

RQ2 asked what task performance is achieved with an ETHD, and also questions how it compares to zero-delay conditions and previous studies. This study answered this question by having users perform the ISO/TS 9241-411 multidirectional tapping task to determine the throughput arising from the No Haptics, Table Haptics and ETHD Haptics Conditions. Table 8.6 summarises the results for the grand throughput and standard deviations for each condition, while Table 8.7 indicated that the ETHD Haptics throughput is lower than the zero-delay conditions with differences of 1.298-1.469bps representing a large effect size. The ETHD Haptics Condition is also noted to be on the lower range compared to previous Fitts's Law studies due to latency in the *Fast ETHD* system (Table 8.8). While the ETHD throughput lagged behind, it is not that far off and can be improved by reducing system latency and training users until they are at expert levels. Considering that users had quite positive sentiment towards this system, as reported in the VR Alien Shooter Game Experiment from Chapter 5, it would be worth improving the ETHD system for optimal user interactions.

8.7 Chapter Summary

This chapters answered RQ2, “*What task performance is achieved with a high-speed ETHD and how does it compare to zero-delay conditions and previous studies?*”, by calculating the grand throughput of the No Haptics, Table Haptics and ETHD Haptics Condition sub-experiments. Comparisons were also made between these conditions and against previous studies. It was noted that the throughput of the ETHD Haptics Condition was on the lower range when compared to other Fitts's Law studies due to the inherent latency in the current ETHD design. However, this could be improved and recommendations are given on how to achieve a more optimal design that would reduce latency. The next chapter will discuss the validity, accuracy and interpretation of the results from the VR Alien Shooter Game Experiment and the VR Fitts's Test Experiment.

Chapter 9

Discussion

This chapter reviews the threats to validity for the results of the VR Alien Shooter Game Experiment and the VR Fitts's Test Experiment, and deals with issues related to construct, internal and external validity to contextualise the discussion related to the results presented in previous chapters.

9.1 Introduction

With results from the VR Alien Shooter Game Experiment and the VR Fitts's Test Experiment having been presented, a general discussion is presented regarding the accuracy and interpretation of the results.

9.2 Threats to validity

The threats to validity for this study are discussed to determine if these results can be trusted and if they apply to all Virtual Reality (VR) users in general. This entails addressing issues related to construct, internal and external validity.

9.2.1 Construct Validity

Construct validity refers to how well a test is able to measure the concept it is designed to evaluate, the VR Alien Shooter Game Experiment making use of the Presence Questionnaire (PQ) to measure immersion and presence, and the User Experience Questionnaire (UEQ) was used to measure User Experience (UX), both

having been used extensively in previous studies. As mentioned in Sections 4.2 and 4.3, Cronbach's alpha is used to measure internal consistency of a scale, the results being 0.81 for the PQ and 0.65-0.89 for the UEQ. These are high values for Cronbach's alpha, and indicate that they are internally consistent and reliable. The VR Fitts's Test Experiment made use of the ISO/TS 9241-411 multidirectional tapping task to measure task performance of user interactions, this standardised test having been used extensively and therefore being trusted to reliably measure human task performance.

The setup for these experiments described in Chapter 3 made use of reliable high quality components from trusted popular online sources. The *Fast ETHD* system itself was tested rigorously in pilot studies by students and staff from the School of Electrical and Information Engineering at the University of the Witwatersrand. This feedback loop from external parties resulted in many hardware and software fixes, performance gains, usability improvements and overall quality enhancement of the system, which was safe and had repeatable behaviour when the experiments were officially opened to participants.

9.2.2 Internal Validity

Internal validity refers to how well the evidence from an experiment can support the conclusions about the cause and effect being studied. For the VR Alien Shooter Game Experiment, only one independent variable changed, the Encountered-Type Haptic Display (ETHD) speed profile, which affected the dependent variables for the categories of the PQ and UEQ. In the VR Fitts's Test Experiment, only one independent variable changed, the Index of Difficulty, which affected the dependent variables of movement time and distance travelled for each haptics condition. Pooling all user movements together for each condition, the independent variable then becomes the haptics condition and the dependent variable the throughput.

To reduce the effects of confounding variables for the VR Alien Shooter Game Experiment, and Table and ETHD Haptics Conditions of the VR Fitts's Test Experiment, the equipment setup and experimental procedure remained the same for each participant, with all users interacting with the same equipment in the same dedicated room. The lighting remained the same due to an LED spotlight improving the ambient lighting of the room even when weather conditions outside of the room caused external lighting to be dim, ensuring optimal lighting conditions for hand tracking at all times. A threat to validity could possibly come from the No Haptics

Condition, where lighting conditions were at the mercy of the current weather and user conditions varied (e.g. height of the virtual control panel). This preliminary experiment was conducted before the full ETHD setup was completed.

To reduce selection bias, only students and staff from the School of Electrical and Information Engineering from the University of the Witwatersrand were invited to participate in the study, this being due to the requirement that participants needed to be computer literate. The participants varied in age, ethnicity, gender, background, left and right handedness, attitudes towards the study, physical and mental capabilities and previous exposure to VR and video games. This was the first exposure to VR for most, the majority of whom were male, which could be regarded as a threat to validity. All the participants' survey responses were considered for the VR Alien Shooter Game Experiment with no cleaning of the data, as the score ranges were consistent with mostly positive sentiments. A few negative sentiments were chosen and these were retained to keep the data as accurate as possible and show what the general population responses would probably be like. The VR Fitts's Test Experiment required participants to be much more active by moving constantly along greater distances, with outliers due to users becoming fatigued, demotivated or not following instructions properly being cleaned using the previously documented methods by Soukoreff and MacKenzie, and Joyce and Robinson [31, 112].

Learning effects were reduced by having training and practice rounds to prepare participants before the main tests started. The experiments were also designed to be as short as possible with maximum data collection so that participants did not become bored or fatigued and lose motivation to continue with their full focus and attention.

Randomisation of the experiment was done on a software level so that neither the participant nor the experimenter knew the order of the treatments for an experiment. This order randomisation occurred every time the *VR Test* application was started up so that the treatment order was different for every participant. This randomisation, in addition to a within-subjects design, was done to further reduce confounding variables and prevent users from seeing a linear increase in speed for the VR Alien Shooter Game Experiment and a linear increase in Index of Difficulty for the VR Fitts's Test Experiment.

9.2.3 External Validity

External validity refers to how well the results from the sample group that took part in a study apply to the greater general population. In this study, the sample group comprised of students and staff who varied in age, ethnicity, gender and background, the majority being students in the age range of 18-25. Participants were computer literate, being a requirement for the target audience for this study, the results therefore being applicable to the broader population who are computer literate. These results may not be fully representative of the general population that include those that are not computer literate, as this subset of the population would require more training to begin with, and would most likely produce less consistent results due to the lack of computer literacy skills.

Another threat to external validity is that use was made of particular components in the experiment setup, with different results possibly being achieved using other VR headsets, or a similar ETHD setup with different motors, linear actuators, microcontrollers and firmware. The hand tracking capabilities alone may vary widely between different VR headsets, these differences potentially leading to changes in latency, accuracy and usability.

With regards to the hand tracking, an LED spotlight was used in this study to maximise the ambient lighting of the room where the experiments were conducted and to optimise the hand tracking accuracy. In real world situations, it is possible that users of ETHD systems could also ensure operating in good lighting conditions. However, there is the possibility that without a dedicated lighting solution, the hand tracking accuracy will be dependent on the time of day and weather conditions.

9.3 Interpretation of Results

The results are discussed for the three experiments in terms of their meeting the two research questions, as well as with respect to local and international literature.

9.3.1 VR Alien Shooter Game Experiment

The results from the VR Alien Shooter Game Experiment show that users did perceive an increase in immersion, presence and UX as the speed profile of the ETHD increased (see Table 5.5), and despite the effect size of these changes being

small, their differences were statistically insignificant. Users' game performance also showed improvement with increasing ETHD speed. Changes that were easily identified visually were for *Quality Of Interface* (Figure E.5) and *Alien Bullets Hit* (Figure E.28), indicating greater user sensitivity to these aspects. To a smaller extent, consistent effects were visually observed for *Total Aliens Hits* (Figure E.17), *Aliens Hit by Normal and Double Shots* (Figure E.20) and *Spaceship Damage* (Figure E.31). Section 5.5 indicated that speed variation analysis on eight out of 10 categories showed improvements in scores with increasing ETHD speed, with an overall sentiment analysis showing that users were positive about the system on all three categories.

The results from this experiment showed that users had a positive and more realistic experience when using ETHD setups, the immersion, presence and UX experienced by users being enhanced by being able to physically interact with the virtual objects they could see. This can make VR experiences much richer and more accurate, and be valuable for areas such as training simulations and live control of teleoperation setups used in medical procedures and mining.

9.3.2 VR Fitts's Test Experiment

The results from the VR Fitts's Test Experiment show that throughput still lags behind for this ETHD setup compared to other zero-latency haptic conditions. However, this is not very far behind, as discussed in Section 8.5, and can be remedied by reducing the latency of the system and training users to expert levels of usage.

User interfaces should be designed to be user-friendly, easy to use and to reduce fatigue. Fitts's Law is useful for designing these interfaces, whether it be for operating systems, websites, physical control panels or VR interfaces. Designing these interfaces with low *ID* values makes this possible to optimise user throughput. The experiment results showed that combining encountered-type haptics with VR interfaces allows users to experience more realistic feedback from VR interfaces and reduces the fatigue that can be caused by mid-air interactions when there is no haptic feedback available.

Although the throughput achieved for the ETHD Haptics Condition when using the Application Selected Target control scheme was lower than other setups, participants had mainly positive responses for the experience and enjoyed taking part in the study, which shows that this technology is worth developing further. Training simulations in VR will benefit from the encountered-type haptic feedback from a system such as the *Fast ETHD*, as the trainees will have a much more realistic experience and

be far better prepared for real world situations. Trainers will also benefit by having flexibility and quick turnaround times regarding changing the objects presented for haptic feedback instead of building entirely new interfaces from scratch.

9.4 Chapter Summary

This chapter discussed the threats to validity and the interpretation of the results for the VR Alien Shooter Game Experiment and the VR Fitts's Test Experiment.

For construct validity, high values of Cronbach's alpha showed that the PQ and UEQ are internally consistent and reliable, while the ISO/TS 9241-411 multidirectional tapping task as a standardised test was trustworthy for measuring task performance. For internal validity, the variables of interest were discussed for both experiments and the design decisions that were made to reduce the effects of confounding variables, selection bias and learning effects. For external validity, the results from this study would mainly be representative of the sub-population that is computer literate, the broader population possibly requiring more training to reach the same level of results.

The results of the VR Alien Shooter Game Experiment showed that while differences between speed profiles were statistically insignificant, participants' perception of immersion, presence and UX grew when the ETHD speed increased, and that the overall sentiment towards the *Fast ETHD* and the experience as a whole was mainly positive. It was observed that the latency arising from the system did not have a negative impact on user sentiment. While the results of the VR Fitts's Test Experiment for the ETHD Haptics Condition lagged behind the zero-delay conditions, the participants still enjoyed the realistic haptic feedback, with the potential for latency to be improved in future designs of the system. Overall, this study has showed that users enjoyed this realistic haptic feedback and that it is worth pushing this technology further.

The following chapter presents the contributions made by this dissertation, makes recommendations for future studies and provides concluding remarks.

Chapter 10

Conclusion

The aim of this study was to investigate the effects that Encountered-Type Haptic Displays (ETHDs) have on user Immersion, Presence, User Experience and Task Performance (IPUXTP) in Virtual Environments (VEs). This dissertation has presented a summary of previous studies on these subjects, the design of experiments to investigate their effects using an ETHD, and their results and discussions. The contributions made from this study are summarised, recommendations for future work outlined and concluding remarks will be made on this study and the future of Virtual Reality (VR).

10.1 Summary of Research Findings

The experiments conducted in this study revealed the findings for two research questions.

RQ1

What effects on immersion, presence and UX are observed in users as ETHD speed increases?

RQ1 Results

An increase in scores for various aspects of the VR experience was observed, with all the results being statistically insignificant. Scores for the *VR Alien Shooter Game Experiment* increased for the PQ aspects of *Possibility To Act* and *Quality Of Interface*, and the UEQ aspect of *Efficiency*, as ETHD speed increased. Game performance was observed to improve in the *Total Aliens Hit*,

Aliens Hit by Normal and Double Shots, Aliens Hit by Laser and Big Shots, Alien Bullets Hit and *Spaceship Damage* categories. No effect was observed on the scores for the UEQ aspect *Attractiveness*, and a negative effect was observed for *Dependability*. Participants had positive sentiments toward the system and the experience as a whole, which was observed in the UEQ average scores of 1.79 for *Perspicuity*, 2.27 for *Stimulation* and 1.33 for *Novelty*.

RQ2

What task performance is achieved with a high-speed ETHD and how does it compare to zero-delay conditions and previous studies?

RQ2 Results

Participants performed the ISO/TS 9241-411 multidirectional tapping task under different haptic conditions for the *VR Fitts's Test Experiment*. The ETHD Haptics Condition resulted in a grand throughput of 2.23bps (SD 0.386), the Table Haptics Condition had 3.53bps (SD 0.436) and the No Haptics Condition yielded 3.70bps (SD 0.476). The ETHD's lower throughput is attributed to the inherent latency in the *Fast ETHD* system.

10.2 Contributions

The following contributions have been made in this dissertation:

- A detailed design of a 2D tabletop *Fast ETHD* system is presented, which focused on speed performance and safety. The literature survey conducted indicated that this is one of the fastest ETHD designs, with the fastest instantaneous speed of $1.64m/s$ having been recorded during its operation.
- The ETHD has been designed with many safety features in mind to protect the user from physical injury, which is possible from such a high speed device. The *Safety Height* feature has been built into the design and training of the system to ensure that the user was protected at all times, while still allowing them to experience maximum immersion, presence and UX.
- At the time of writing, this appears to be the first study to investigate how encountered-type haptics affects user immersion, presence and UX. The VR

Alien Shooter Game Experiment also makes use of the Presence Questionnaire (PQ) and User Experience Questionnaire (UEQ) in a unique way by identifying subsets of the questions that could be affected by ETHD speed and analysing the results from the ratings for different ETHD speed profiles. The results show a small increase in user scores for immersion, presence, UX and game performance for eight out of 10 categories of the PQ, UEQ and game scores, with the overall user sentiment on the system and experience being positive.

- At the time of writing, it appears that this is the first study done that aims to evaluate an ETHD using Fitts's Law. The VR Fitts's Test Experiment is the first instance of the ISO/TS 9241-411 multidirectional tapping task being used to determine the throughput of an ETHD, which is important to determine how useful these devices can be to users when compared to other well-established HCI devices, such as the computer mouse. The ETHD Haptics Condition yielded a throughput of 2.23bps, which is 1.298-1.469bps less than the Table Haptics and No Haptics conditions, and at the lower end of the computer mouse.
- A paper titled *Determining Human Hand Performance with the Oculus Quest in Virtual Reality using Fitts's Law* was submitted for the SAICSIT 2021 conference, where it was presented and published in its proceedings [43]. The paper presented the results from the No Haptics Condition of the VR Fitts's Test Experiment, where the hand tracking feature of the Oculus Quest was evaluated using the ISO/TS 9241-411 multidirectional tapping task to determine the throughput of the feature.

These results and contributions are valuable to the field of encountered-type haptics and would greatly benefit future research in this field to build better ETHD designs and to improve results.

10.3 Recommendations for Future Research

10.3.1 Latency

The latency of the encountered-type haptic feedback system needs to be improved, and while the *Fast ETHD* system was designed to be as fast as possible, with the ETHD reaching speeds of up to $1.64m/s$, the latency that occurs when switching button targets and having users wait for the target to become available reduces the

IPUXTTP of users. The latency does not appear to stem from the communication between the *VR Test* and *Quest2CoreBridge* applications, and if it can be reduced between these applications, will be the result of programming optimisations and faster networking communications, possibly from the newer WiFi6 devices. The latency of the system appears to mainly stem from the g2core firmware on the Arduino Due and the motors. The g2core firmware is a stable and mature firmware for Computer Numeric Control (CNC) applications, its primary workflow being the sequential execution of G-code commands for tasks such as milling and laser cutting, its focus therefore being more on accuracy than responding to sudden changes in the sequence of commands. It is recommended that the g2core firmware be modified to enable a quick response to such real-time changes ,or that another CNC firmware is used that has this capability. A microcontroller that is faster than the Arduino Due would also aid in dealing with rapid changes in commands.

Latency cannot be completely removed, as the ETHD is a mechanical device, and while moving the rig from point to point even faster would be welcome, it would also bring further challenges, such as keeping the system stable and in place, requiring more robust safety features to be built into the system. As observed in the VR Fitts’s Test Experiment, the control scheme can also make all the difference to the user experience. Currently, the Application Selected Target control scheme reduces the wait time to click on the next button considerably, to the point that for most users, it is as if the button is “already there”. However, this experiment had an easily predictive sequence for the rig to follow. A control scheme that would incorporate predictive methods to accurately guess the user’s next move, such as eye tracking, hand trajectory analysis and machine learning, would improve the experience by getting the rig to move to the target position well before the user reaches the new button. An example of such a predictive model that could be useful in reducing this latency is the REACH+ framework by Gonzalez *et. al* [126].

10.3.2 Safety System

The *Safety Height* feature of the *Fast ETHD* system protected users from bumping into the rig when it was in motion, but it is not perfect and could be improved upon. In terms of safety, if the rig is in motion and the user moves their hand below the *Safety Height*, the command to stop the rig motion is immediately sent and repeated until the user moves their hand above it again. However, this will rapidly decelerate the rig until it is stationary rather than stopping it at the very same instant, which means that there is still a small chance of users bumping into it. Such a rapid

deceleration would need components that could handle the speed change, and require the rig as a whole to handle the forces arising from it so that it does not move out of place.

The *Safety Height* workflow also requires some training and for users to wait for the rig to stop at a new target, which will impact their immersion, presence and UX. This feature should be improved to make the rig movements more seamless and less obvious, so that the users' experience is not negatively impacted.

10.3.3 Modifications to the PQ and UEQ

Modifications to the PQ and UEQ were made for the VR Alien Shooter Game Experiment where specific categories were identified that would be potentially affected by ETHD speed. As seen from the results of this experiment, one of the categories showed no effect from varying speed, while another showed a small negative effect. This was the first time that these questionnaires were used in this manner, and further work on these questionnaires, or developing new ones, is recommended to be used for studies where the goal is to determine how responses change as a variable is altered.

10.3.4 Hand tracking

The hand tracking on the Oculus Quest 1 used in this study was acceptable, this device having been superseded by its more recent successor, the Meta Quest 2, with more devices planned. The sampling rate of the Leap Motion Controller is far superior to that of the Quest 1, with more accurate hand tracking being beneficial for future studies, and researchers possibly exploring the current range of devices available that offer this feature.

In this study, the participants only used the index fingertip of their dominant hand to click on buttons and this sometimes resulted in having to advise participants to gesture their hand in a specific way that may not have been natural. It is recommended that future studies try to incorporate both hands, all parts of all the fingers and a wider variety of gestures to make the experience feel more natural.

10.3.5 Virtual Space

The *Fast ETHD* system limits users to exploring the virtual environment in a 2D space. This design was selected due to time and financial constraints and to simplify the scope of the study. It is recommended that future studies try to extend the *Fast ETHD* system so that it can operate in 3D for a larger virtual area for users to explore with encountered-type haptic feedback. Robotic arms with 6 Degrees of Freedom (DOF) can do this but have financial limitations due to the cost, so extending the *Fast ETHD* system would be a far cheaper option as there are many CNC gantry configurations that accommodate movements in 3D space.

10.3.6 Replicating the study

Guidelines are given in Chapter 3 on how to build the *Fast ETHD* system. It may not be desirable to utilise the exact components used for this study if there are better options available, and while this means that the same setup will not be used, replicating the study in a similar way will be beneficial to its external validity by comparing results and observing how it generalises to the greater population. As mentioned earlier, this study limited its participants to those who were already computer literate, it may therefore be worthwhile conducting this study with those who are not to see how these two groups compare.

Another recommendation is to allow users to reach expert levels before conducting the tests, which may lengthen the experiment procedure, but could potentially produce better results than what has been observed from the novice subjects in this study.

10.4 Concluding Remarks

This dissertation has shown how ETHDs affect the IPUXTP of users interacting with a VE with encountered-type haptic feedback, with the results indicating positive attitudes towards this technology, and how beneficial it can be for real-time use in work environments when implemented correctly. This technology is significant in the field of VR and studies with similar approaches to the one taken here are being undertaken. The HapticPanel study by van Deurzen *et al.* has a similar setup to the *Fast ETHD* system, it being upright and having a smaller workspace [127]. It is slower, at a maximum speed of 0.241m/s, but appears to have lower system latency

for the smaller distances between buttons. This system also requires the user to wear a tracking device on their finger, for the OptiTrack Motive hand tracking software that is used. More equipment is needed for this setup, which makes it less natural, but system latency appears to be lower, and different approaches such as this one would be interesting to consider to enhance ETHD designs to almost zero-latency levels of performance.

VR technology in the past was enjoyed by a few individuals privileged enough to have had the experience, while today this technology is much cheaper and widespread. It is not in every consumer home as yet, but can easily be found in arcades and restaurants at an affordable fee, or sometimes at no cost, to enjoy the experience. The latest consumer version of the Quest, the Meta Quest 2, is available online for approximately \$400 (at the time of writing), which is still much cheaper than many flagship phones, gaming PC's, and the latest Playstation 5 and Xbox Series X consoles. These headsets can introduce users to entirely new and novel experiences that these other devices cannot offer.

For many of the participants of this study, and the individuals involved in testing the equipment during its development, this was their first experience with VR. The positivity around the experiment and the experience has been overwhelming, with many of these individuals having the opportunity to try out the games on the Quest, these new experiences sparking many interesting discussions on the future of this technology and its applications, from entertainment and beyond. Users enjoyed the added haptic feedback component of the study, whether it was the simple flat table, or the realistic buttons of the ETHD.

VR is no longer just a niche or novelty, its uses in creating art, designs, simulations and training continuing to grow as the technology develops even further. Improving haptic feedback technology will aid the ultimate goal of VR, in which the virtual experience is indistinguishable from reality. It is the next step in the evolution of HCI and computing that can bring more capability to the user than some of its predecessors, such as the humble but effective computer mouse and keyboard. To paraphrase the ending monologue of the protagonist Neo, from the motion picture *The Matrix*, in which future humans are plugged into a VR simulation of the real world, VR is "...a world without borders or boundaries, a world, where anything is possible. Where we go from there, is a choice I leave to you..." [22].

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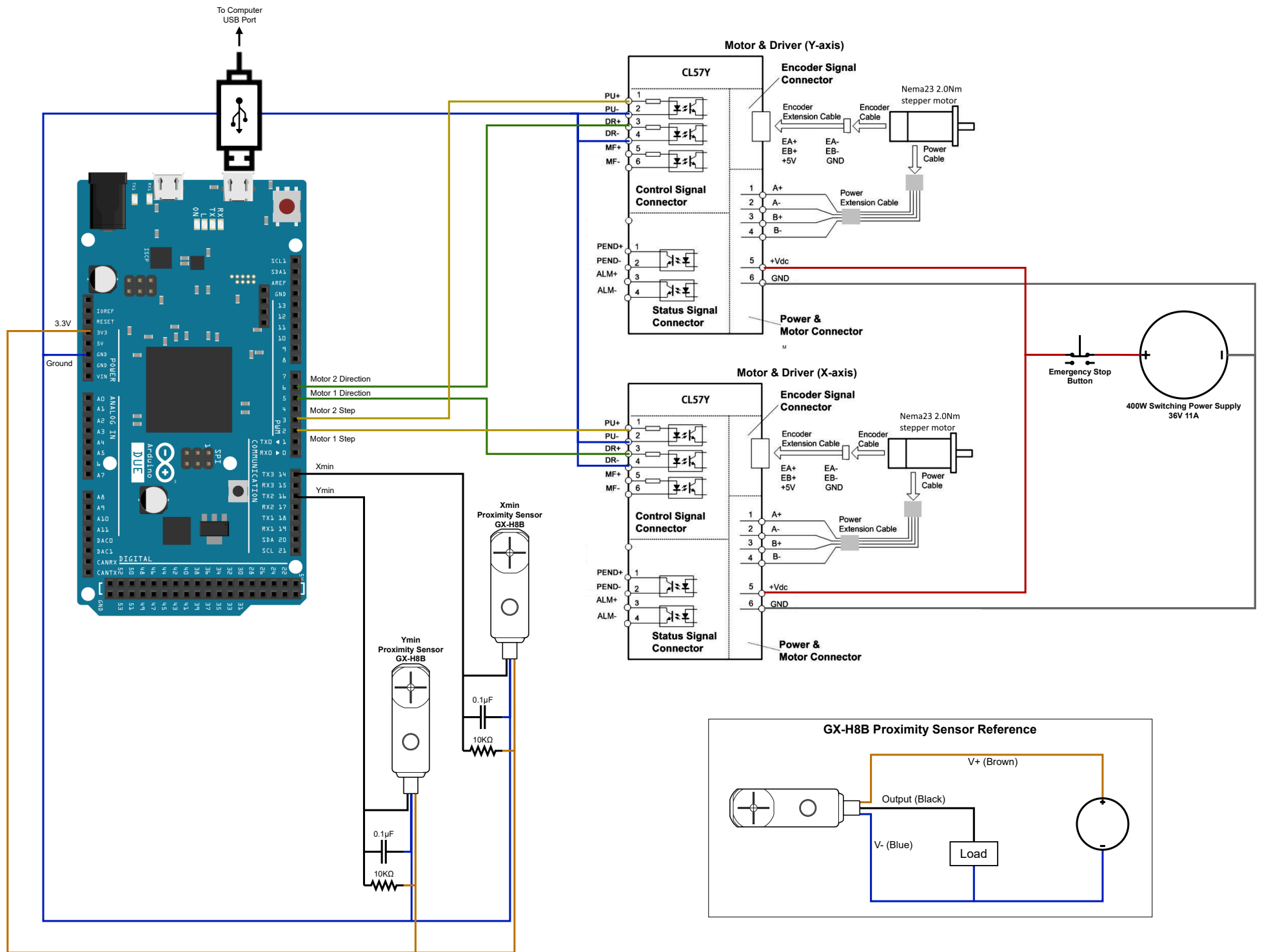
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Appendix A

Hardware Wiring

The following is the wiring diagram for the motor and proximity sensor connections to the Arduino Due flashed with the g2core firmware. A reference pinout diagram for the Arduino Due microcontroller board flashed with the g2core firmware is provided at <https://github.com/synthetos/g2/wiki/Arduino-DUE-Pinout-for-g2core>.



Appendix B

Witmer-Singer Presence Questionnaire

The Witmer-Singer Presence Questionnaire uses a seven point Likert Scale to determine the immersion and presence experienced by a user [32]. Questions are grouped into categories for *Realism*, *Possibility to act*, *Quality of interface*, *Possibility to examine*, *Self-evaluation of performance*, *Sounds* and *Haptic*. The document provides the scoring system used to evaluate scores per category.

PRESENCE QUESTIONNAIRE

(Witmer & Singer, Vs. 3.0, Nov. 1994)*

Revised by the UQO Cyberpsychology Lab (2004)

Characterize your experience in the environment, by marking an "X" in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer.

WITH REGARD TO THE EXPERIENCED ENVIRONMENT

1. How much were you able to control events?

NOT AT ALL		SOMEWHAT			COMPLETELY	

2. How responsive was the environment to actions that you initiated (or performed)?

NOT RESPONSIVE		MODERATELY RESPONSIVE			COMPLETELY RESPONSIVE	

3. How natural did your interactions with the environment seem?

EXTREMELY ARTIFICIAL		BORDERLINE			COMPLETELY NATURAL	

4. How much did the visual aspects of the environment involve you?

NOT AT ALL		SOMEWHAT			COMPLETELY	

5. How natural was the mechanism which controlled movement through the environment?

EXTREMELY ARTIFICIAL		BORDERLINE			COMPLETELY NATURAL	

6. How compelling was your sense of objects moving through space?

NOT AT ALL			MODERATELY COMPELLING			VERY COMPELLING

7. How much did your experiences in the virtual environment seem consistent with your real world experiences?

NOT CONSISTENT			MODERATELY CONSISTENT			VERY CONSISTENT

8. Were you able to anticipate what would happen next in response to the actions that you performed?

NOT AT ALL			SOMEWHAT			COMPLETELY

9. How completely were you able to actively survey or search the environment using vision?

NOT AT ALL			SOMEWHAT			COMPLETELY

10. How compelling was your sense of moving around inside the virtual environment?

NOT COMPELLING			MODERATELY COMPELLING			VERY COMPELLING

11. How closely were you able to examine objects?

NOT AT ALL			PRETTY CLOSELY			VERY CLOSELY

12. How well could you examine objects from multiple viewpoints?

NOT AT ALL			SOMEWHAT			EXTENSIVELY

13. How involved were you in the virtual environment experience?

|_____|_____|_____|_____|_____|_____|_____|
NOT INVOLVED MILDLY INVOLVED COMPLETELY ENGROSSED

14. How much delay did you experience between your actions and expected outcomes?

|_____|_____|_____|_____|_____|_____|_____|
NO DELAYS MODERATE DELAYS LONG DELAYS

15. How quickly did you adjust to the virtual environment experience?

|_____|_____|_____|_____|_____|_____|_____|
NOT AT ALL SLOWLY LESS THAN
ONE MINUTE

16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

|_____|_____|_____|_____|_____|_____|_____|
NOT PROFICIENT REASONABLY PROFICIENT VERY PROFICIENT

17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

|_____|_____|_____|_____|_____|_____|_____|
NOT AT ALL INTERFERED PREVENTED
SOMEWHAT TASK PERFORMANCE

18. How much did the control devices interfere with the performance of assigned tasks or with other activities?

|_____|_____|_____|_____|_____|_____|_____|
NOT AT ALL INTERFERED INTERFERED
SOMEWHAT GREATLY

19. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

|_____|_____|_____|_____|_____|_____|_____|
NOT AT ALL SOMEWHAT COMPLETELY

IF THE VIRTUAL ENVIRONMENT INCLUDED SOUNDS:

20. How much did the auditory aspects of the environment involve you?

|_____|_____|_____|_____|_____|_____|
NOT AT ALL SOMEWHAT COMPLETELY

21. How well could you identify sounds?

|_____|_____|_____|_____|_____|_____|
NOT AT ALL SOMEWHAT COMPLETELY

22. How well could you localize sounds?

|_____|_____|_____|_____|_____|_____|
NOT AT ALL SOMEWHAT COMPLETELY

IF THE VIRTUAL ENVIRONMENT INCLUDED HAPTIC (SENSE OF TOUCH):

23. How well could you actively survey or search the virtual environment using touch?

|_____|_____|_____|_____|_____|_____|
NOT AT ALL SOMEWHAT COMPLETELY

24. How well could you move or manipulate objects in the virtual environment?

|_____|_____|_____|_____|_____|_____|
NOT AT ALL SOMEWHAT EXTENSIVELY

Last version : March 2013

*Original version : Witmer, B.G. & Singer, M.J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence : Teleoperators and Virtual Environments*, 7(3), 225-240. Revised factor structure: Witmer, B.J., Jerome, C.J., & Singer, M.J. (2005). The factor structure of the Presence Questionnaire. *Presence*, 14(3) 298-312.

Questionnaire sur l'État de Présence (QÉP)

Laboratoire de Cyberpsychologie de l'UQO

Validation of the French-Canadian version developed by the UQO Cyberpsychology Lab:

- 101 participants completed the questionnaire following an immersion in a virtual environment;
- Cronbach's Alpha = .84
- Now 19 items (for VEs without sound/touch) et 24 items (for VEs with sounds/touch)

Scoring :

Total : Items 1 to 19 (reverse items 14, 17, 18)

- « Realism » : Items 3 + 4 + 5 + 6 + 7 + 10 + 13
- « Possibility to act » : Items 1 + 2 + 8 + 9
- « Quality of interface » : Items (all reversed) 14 + 17 + 18
- « Possibility to examine » : Items 11 + 12 + 19
- « Self-evaluation of performance » : Items 15 + 16
- « Sounds* » : Items 20 + 21 + 22
- « Haptic* » : Items 23 + 24

* NOTE : Scoring of « sounds » and « haptic » are not part of the factor analysis of the French version.

Norms (French version) :

	Moyenne	Écart type
Total	104.39	18.99
« Realism »	29.45	12.04
« Possibility to act »	20.76	6.01
« Quality of interface »	15.37	5.15
« Possibility to examine»	15.38	4.90
« Auto-évaluation de la performance »	11.00	2.87

Last version : March 2013

*Original version : Witmer, B.G. & Singer, M.J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence : Teleoperators and Virtual Environments*, 7(3), 225-240. The factor structure of the Presence Questionnaire. *Presence*, 14(3) 298-312. Revised factor structure: Witmer, B.J., Jerome, C.J., & Singer, M.J. (2005). The factor structure of the Presence Questionnaire. *Presence*, 14(3) 298-312.

Appendix C

User Experience Questionnaire

The User Experience Questionnaire uses a seven point Likert Scale to numerically evaluate user experience [37]. Questions are grouped into scales for *Attractiveness*, *Efficiency*, *Perspicuity*, *Dependability*, *Stimulation* and *Novelty*. An Excel spreadsheet and handbook provided by the official UEQ website <https://www.ueq-online.org/> provides the scoring system used to evaluate scores per scale [128].

Please make your evaluation now.

For the assessment of the product, please fill out the following questionnaire. The questionnaire consists of pairs of contrasting attributes that may apply to the product. The circles between the attributes represent gradations between the opposites. You can express your agreement with the attributes by ticking the circle that most closely reflects your impression.

Example:

attractive	☐	☒	☐	☐	☐	☐	☐	unattractive
------------	-----------------------	----------------------------------	-----------------------	-----------------------	-----------------------	-----------------------	-----------------------	--------------

This response would mean that you rate the application as more attractive than unattractive.

Please decide spontaneously. Don't think too long about your decision to make sure that you convey your original impression.

Sometimes you may not be completely sure about your agreement with a particular attribute or you may find that the attribute does not apply completely to the particular product. Nevertheless, please tick a circle in every line.

It is your personal opinion that counts. Please remember: there is no wrong or right answer!

Please assess the product now by ticking one circle per line.

[illegible]

Additional Questions for the KPI Extension of the UEQ

To calculate a meaningful KPI for the UEQ 6 questions must be added to the questionnaire. See the UEQ handbook for details.

The KPI extension is described in detail in:

Hinderks, A., Schrepp, M., Domínguez Mayo, F.J., Escalona, M.J., Thomaschewski, J. (2019). Developing a UX KPI based on the User Experience Questionnaire. Computer Standards & Interfaces. <https://doi.org/10.1016/j.csi.2019.01.007>.

Please note that the 6 additional questions are currently not available for all UEQ language versions. This document will be updated whenever new translations will be available.

English version

Scale	Question
Attractiveness	The product should look attractive, enjoyable, friendly and pleasant.
Efficiency	I should perform my tasks with the product fast, efficient and in a pragmatic way.
Perspiciuity	The product should be easy to understand, clear, simple, and easy to learn.
Dependability	The interaction with the product should be predictable, secure and meets my expectations.
Stimulation	Using the product should be interesting, exiting and motivating.
Novelty	The product should be innovative, inventive and creatively designed.

German version

Scale	Question
Attractiveness	Das Produkt soll attraktiv, angenehm und sympathisch wirken.
Efficiency	Das Produkt soll mir helfen, meine Aufgaben schnell, effizient und pragmatisch zu erledigen.
Perspiciuity	Das Produkt soll übersichtlich, verständlich und leicht zu lernen sein.
Dependability	Die Bedienung des Produkts soll in der Bedienung vorhersehbar und gut kontrollierbar sein.
Stimulation	Das Arbeiten mit dem Produkt soll interessant, spannend und aktivierend sein.
Novelty	Das Produkt soll originell, innovativ und kreativ gestaltet sein.

Appendix D

Participant Information Sheets and Consent Forms

Participant Information Sheets and Consent Forms were given to volunteers to read and sign before they could take part in the experiments. The following are the forms explaining the VR Alien Shooter Game Experiment and the No Haptics, Table Haptics and ETHD Haptics Conditions for the VR Fitts's Test Experiment.

Participant Information Sheet

UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG



Study Title: Determining Human Hand Performance in Virtual Reality using Fitt's Law

Introduction and purpose of this study

Dear Sir / Madam

My name is Kiren Padayachee and I am a Masters student at the School of Electrical and Information Engineering at the University of the Witwatersrand in Johannesburg. As part of my studies, I am undertaking an investigation into the performance of the human hand as a computer interaction device.

I would like to invite you to take part in an experiment in which you will be interacting with a Virtual Reality (VR) application using the Oculus Quest headset to view the virtual environment. The Oculus Quest has the capability to track hand movements and this enables the user to use their hands as an interaction device. The full experiment procedure should take around 20 minutes.

Experiment Procedure

The experiment will require you enter information for your age, gender and dominant hand. A VR version of the Fitt's Test will then be presented, requiring you to click on buttons in the virtual environment in a specified order. The VR Fitt's Test is depicted in Figure 1. The data recorded for this test will be movement times and accuracy.

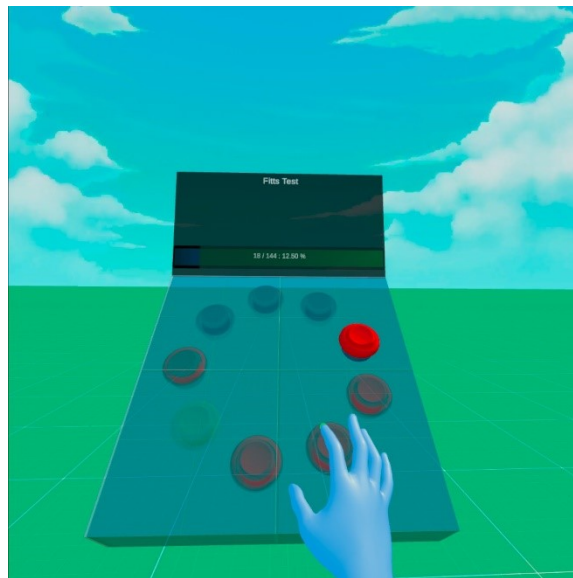


Figure 1. User view of the virtual reality Fitt's Test

Risks and safety measures

This experiment requires the user to move their arm constantly which could cause a mild amount of fatigue however regular break times are included in the test to allow the user to rest.

You will not receive any direct benefits from participating in this research, and there are no disadvantages or penalties for not participating. You may withdraw from the study at any time without penalty. Partaking in the experiment will be completely confidential and anonymous as you will not be required to submit your name or any identifying information. The experiment will not contain any personal questions to answer except for age, gender and dominant hand information required for statistical analysis purposes. The information recorded

from the experiments will be held securely in a private database and will not be disclosed to anyone else. If you experience any distress or discomfort at any point during the experiment, we will, at your discretion, temporarily, or permanently stop the process. You may also elect to resume at another time.

Research results

The results achieved after analysis of the data captured during this research will be recorded in my final Masters dissertation. The dissertation will be added to Wits WIREDSpace (<http://wiredspace.wits.ac.za/>) so that it is easily available to the general public. My intention is to also publish this research in engineering journals and to present the research at conferences. If you would like a copy of the dissertation you can indicate this on the consent form.

Communication channels

If you have any questions about this research, feel free to contact me or my supervisors anytime during the research process on the details listed below. If you have any concerns or complaints regarding the ethical procedures of this study, you are welcome to contact representatives of the University Human Research Ethics Committee (Non-Medical).

Researcher: Kiren Padayachee, 0209281M@students.wits.ac.za, 084 952 4180

Supervisor: Dr. Stephen Levitt, Stephen.Levitt@wits.ac.za, 011 717 7209

Supervisor: Prof. Ken Nixon, Ken.Nixon@wits.ac.za, 011 717 7203

Human Research Ethics Committee (Non-Medical): Charmaine Khumalo, Charmaine.khumalo@wits.ac.za, 011 717 1788

Yours sincerely,
Kiren Padayachee

Consent Form

UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG



Study Title: Determining Human Hand Performance in Virtual Reality using Fitt's Law

Researcher: Kiren Padayachee

I,, agree to participate in this research study. The research has been explained to me and I understand what my participation will involve. Please circle the relevant options below.

I choose to take part in the experiment named "Determining Human Hand Performance in Virtual Reality using Fitt's Law"	YES	NO
I agree that my participation will remain confidential	YES	NO
I agree that I have been informed that I will be required to use Virtual Reality equipment	YES	NO
I agree to have my movement time and accuracy data recorded during the experiment	YES	NO
I agree to disclose my age, gender and dominant hand information	YES	NO
I agree to have the above recorded data stored in a database	YES	NO
I agree that the information I provide may be used anonymously by other researchers following this study	YES	NO
I confirm that I have not been diagnosed or been in contact with anyone diagnosed with Covid-19 in the last 14 days.	YES	NO
I can confirm that I am not displaying any symptoms of Covid-19 at the time of the experiment (dry cough, fever, loss of taste and smell, etc.)	YES	NO
Temperature taken (°C)		
I would like to be contacted about further studies related to this study	YES	NO
I would like to receive a copy of the Masters dissertation once completed	YES	NO

..... (signature)

..... (name of participant)

..... (date)

..... (cellphone number - if you wish to be contacted for further studies or to receive a copy of the Masters dissertation)

..... (email address - if you wish to be contacted for further studies or to receive a copy of the Masters dissertation)

..... (signature)

..... (name of researcher)

..... (date)

Participant Information Sheet



Project Title: The Effects of Minimal and Encountered-Type Haptics on Immersion, Presence, User Experience and Task Performance in Virtual Control Panel Environments

Introduction and purpose of this study

Dear Sir / Madam

My name is Kiren Padayachee and I am a Masters student at the School of Electrical and Information Engineering at the University of the Witwatersrand in Johannesburg. As part of my studies, I am undertaking a research project to investigate how different types of haptics (or touch feedback) affect immersion, presence and user experience in Virtual Reality (VR) applications. An Encountered-Type Haptic Device (ETHD) will be used as part of this investigation. These devices dynamically track users to provide touch feedback. The ETHD for this study will track users in two dimensions. The real objects attached to the ETHD will enable you to physically “feel” the virtual buttons on a virtual control panel. As you move your hand above these virtual objects, the ETHD will align the correct real object to the virtual object’s position that you intend to interact with. Figure 1 depicts how this operation will work.

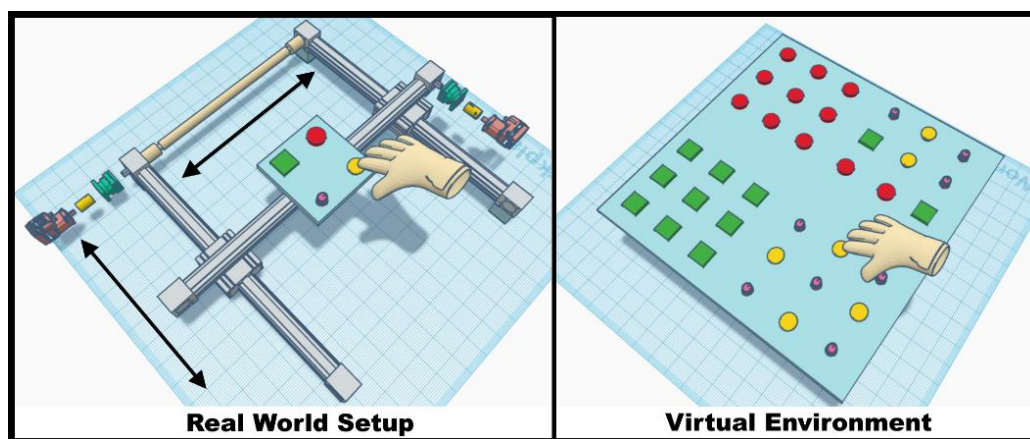


Figure 1. Encountered-Type Haptic Device operation

As part of this project, I would like to invite you to take part in any of three experiments in which you will be interacting with a VR application using the Oculus Quest VR headset to view the virtual environment and a table or ETHD for touch feedback. Each test will require approximately 30 minutes to complete.

Experiment 1: Investigating the Effects of Minimal Haptics on Task Performance in a Virtual Control Panel Environment

For this experiment, you will be interacting with a VR version of Fitts’s Test, which requires you to click on buttons in the virtual environment in a specified order as fast as possible. A regular flat table will provide minimal haptic feedback. The data recorded for this test will be your movement times and accuracy. The VR Fitts’s Test is depicted in Figure 2.

Experiment 2: Investigating the Effects of Encountered-Type Haptics on Task Performance in a Virtual Control Panel Environment

For this experiment, you will again be interacting with a VR version of Fitts’s Test, which requires you to click on buttons in the virtual environment in a specified order as fast as possible. An ETHD will provide dynamic and realistic haptic feedback. The data recorded for this test will be your movement times and accuracy.

Experiment 3: Investigating the Effects of Encountered-Type Haptic Device Speed on Immersion, Presence and User Experience in a Virtual Control Panel Environment

Experiment 3 will involve the ETHD tracking your hand at different speeds as you interact with the virtual control panel to play an alien shooting arcade game. You will be required to answer a questionnaire to rate your experience as part of the activity. The alien shooting arcade game is depicted in Figure 2.

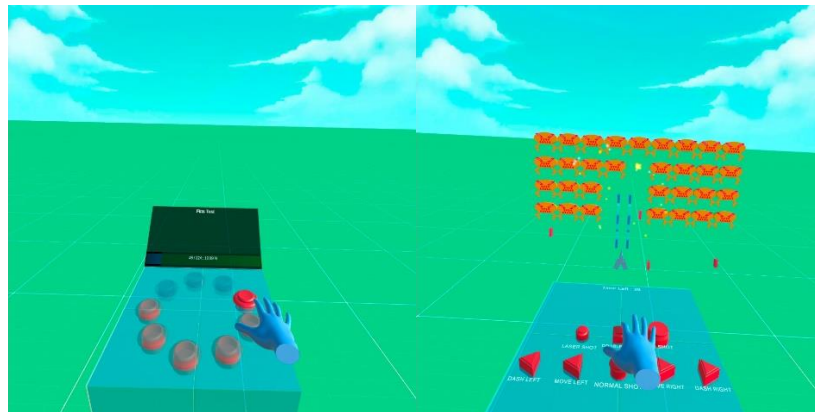


Figure 2. In-app screenshots of Fitts's Test (left) and the alien shooting arcade game (right)

Risks and safety measures

It must be noted that the ETHD is a mechanical device with moving parts, therefore there exists a small chance of injury due to accidental collisions with the device. However, measures are implemented into the system to ensure your safety. The status of the ETHD's motion will be displayed to you at all times. You may only reach down to interact with the real objects on the ETHD when it is completely stationary. The ETHD will automatically stop its motion if you get close to it. As an additional measure, you will constantly be monitored by myself, and I will immediately switch off the ETHD should you get too close to it while it is in motion. The ETHD's maximum speed will be limited to the typical speed capabilities of normal human hand motion. You may view the operation of the ETHD at the following link <https://drive.google.com/file/d/1SfsTjII3ITQF4yVosWT25mzp9LLD55D7/view>.

You will not receive any direct benefits from participating in this research, and there are no disadvantages or penalties for not participating. Participants who complete an experiment will, however, be offered further time to familiarise themselves with the VR headset through preloaded games. You may withdraw from the study at any time without penalty. Partaking in the experiment will be completely confidential as I will not be asking for your name or any identifying information. The experiment will not contain any personal questions to answer except for age, gender and dominant hand information required for statistical analysis purposes. The information recorded from the experiments will be held securely in a private database and will not be disclosed to anyone else. If you experience any distress or discomfort at any point during the experiment, we will, at your discretion, temporarily, or permanently stop the process. You may also elect to resume at another time.

Research results

The results achieved after analysis of the data captured during this research will be recorded in my final Masters dissertation. The dissertation will be added to Wits WIREDSpace (<http://wiredspace.wits.ac.za/>) so that it is easily available to the general public. My intention is to also publish this research in engineering publications and to present the research at conferences.

Communication channels

If you have any questions about this research, feel free to contact me or my supervisors anytime during the research process on the details listed below. If you have any concerns or complaints regarding the ethical procedures of this study, you are welcome to contact representatives of the University Human Research Ethics Committee (Non-Medical).

Researcher: Kiren Padayachee, 0209281M@students.wits.ac.za, 084 952 4180

Supervisor: Dr. Stephen Levitt, Stephen.Levitt@wits.ac.za, 011 717 7209

Supervisor: Prof. Ken Nixon, Ken.Nixon@wits.ac.za, 011 717 7203

Human Research Ethics Committee (Non-Medical): Charmaine Khumalo, Charmaine.khumalo@wits.ac.za, 011 717 1788

Yours sincerely,
Kiren Padayachee

Consent Form

UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG



Project Title: Encountered-Type Haptic Device Speed Effects on Immersion, Presence, User Experience and Task Performance in Virtual Control Panel Environments

Researcher: Kiren Padayachee

I,, agree to participate in this research project. The research has been explained to me and I understand what my participation will involve. Please circle the relevant options below.

I choose to take part in Experiment 1: Investigating the Effects of Minimal Haptics on Task Performance in a Virtual Control Panel Environment	YES	NO
I choose to take part in Experiment 2: Investigating the Effects of Encountered-Type Haptics on Task Performance in a Virtual Control Panel Environment	YES	NO
I choose to take part in Experiment 3: Investigating the Effects of Encountered-Type Haptic Device Speed on Immersion, Presence and User Experience in a Virtual Control Panel Environment	YES	NO
I agree that my participation will remain confidential	YES	NO
I agree that I have been informed that I will be required to use Virtual Reality equipment	YES	NO
I agree that I have been informed that I will be interacting with a moving mechanical device	YES	NO
I agree that I am aware that there may be potential for injury to myself and that I have been notified of the risks and safety measures in place	YES	NO
I agree to have my movement time and accuracy data recorded during Experiment 1 and 2	YES	NO
I agree to rating my experience of Experiment 3 through a questionnaire	YES	NO
I agree to disclose my age, gender and dominant hand information	YES	NO
I agree to have the above recorded data stored in a database	YES	NO
I agree that the information I provide may be used anonymously by other researchers following this study	YES	NO
I can confirm that I am not displaying any symptoms of Covid-19 at the time of the experiment (dry cough, fever, loss of taste and smell, etc.)	YES	NO
Temperature taken (°C)		

..... (signature)

..... (name of participant)

..... (date)

..... (signature)

..... (name of researcher)

..... (date)

Appendix E

Speed Variation Analysis Results for the VR Alien Shooter Game Experiment

This appendix presents the detailed results and analysis for the VR Alien Shooter Game Experiment. Results were analysed per speed profile for the PQ scales of *Possibility To Act* and *Quality Of Interface*, the UEQ scales of *Attractiveness*, *Efficiency* and *Dependability*, and the user game performance data for *Total Aliens Hit*, *Aliens Hit By Normal And Double Shots*, *Aliens Hit By Laser And Big Shots*, *Alien Bullets Hit* and *Spaceship Damage*. The final conclusions for this analysis are presented in Section 5.4.2.

E.1 Immersion and Presence - Possibility To Act

The four questions for *Possibility To Act* from the PQ, when averaged with Equation 5.3, resulted in 25 possible ordinal score outcomes within the range of -3 to +3, with an interval of 0.25 between values. These final score value frequencies are reported in Figure E.1 for each speed profile. Means and standard deviations are summarised in Table E.1. These score averages and data distributions are visualised in Figure E.2. The score averages for all speed profiles indicated positive sentiment in this scale. A slight increase in scores was observed as the speed profile was increased.

The Kruskal-Wallis test was then done and resulted in $\chi^2 = 0.234$ and p -value = 0.972, indicating no significant differences in means. A result of $\eta^2 = -0.0288$ indicated a small effect size. Results from Dunn's test (summarised in Table E.2) also indicated no significant differences between speed profile pairs. It was noted

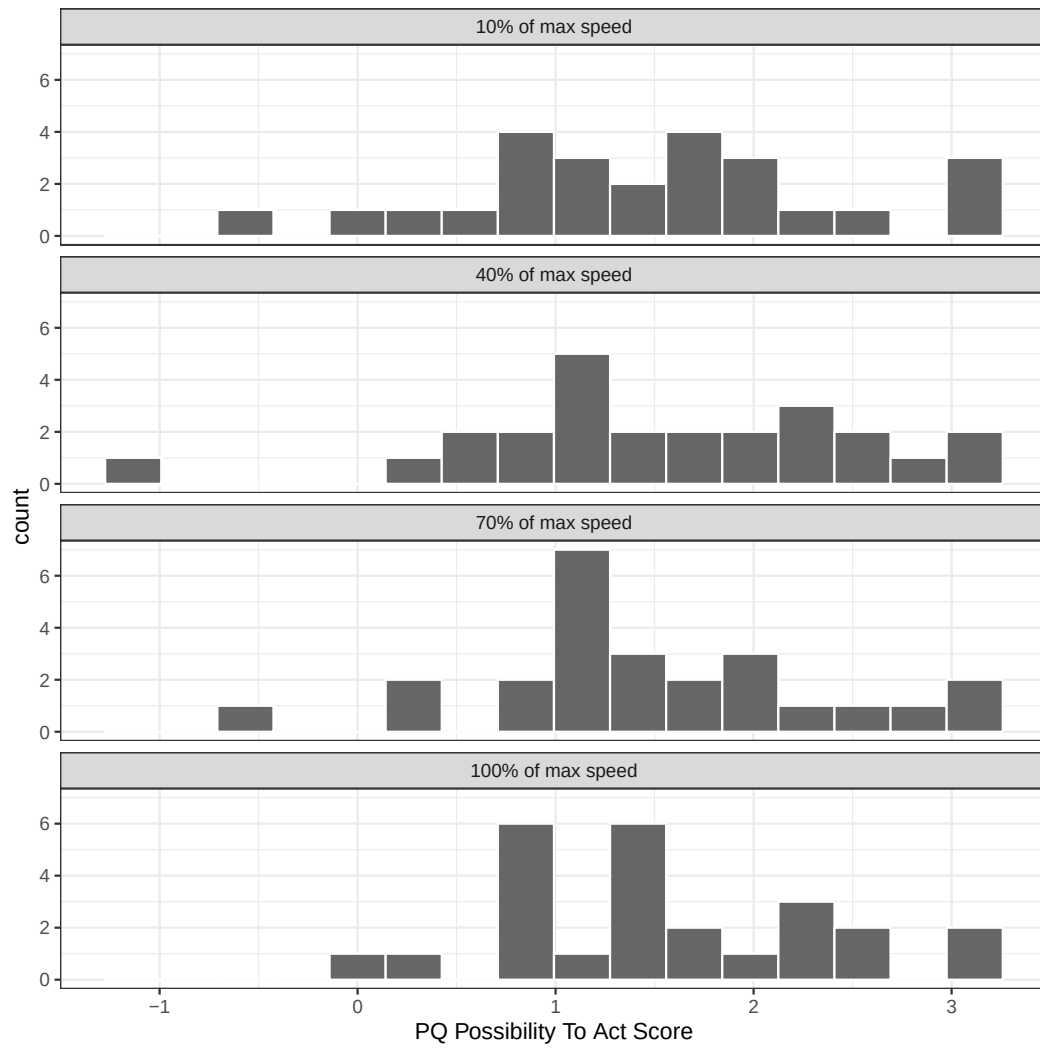


Figure E.1: Possibility To Act score frequencies for each speed profile

Table E.1: Mean scores and standard deviation results for 10%, 40%, 70% and 100% ETHD speed profiles on Possibility To Act

Speed Profile	Mean	Standard Deviation
10%	1.44	0.936
40%	1.53	0.985
70%	1.49	0.855
100%	1.52	0.816

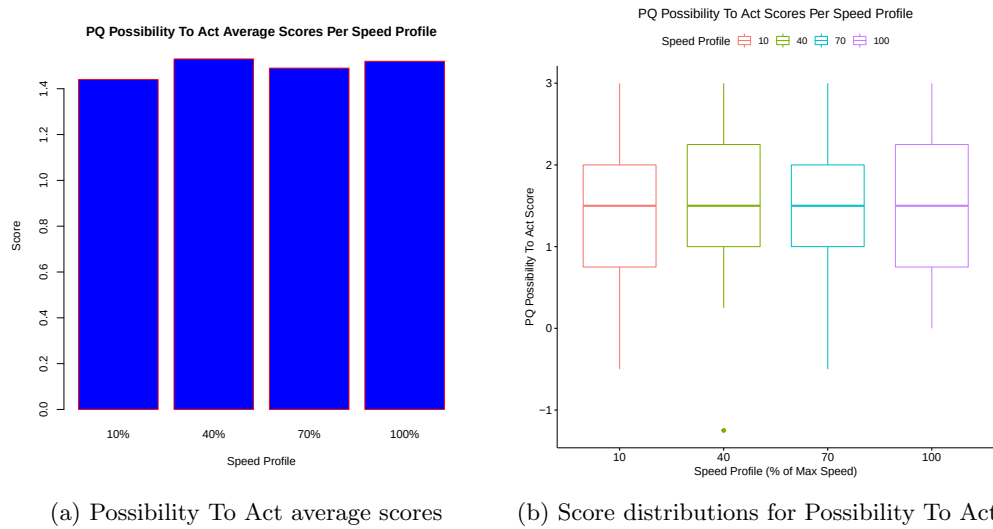


Figure E.2: Score averages and distributions for the Possibility To Act from the PQ

Table E.2: Multiple pairwise-comparison results from Dunn's test for 10%, 40%, 70% and 100% ETHD speed profiles on Possibility To Act

Test Pair	Mean Difference	Mean Difference %	z-statistic	p-value	Significantly Different?
10-40	0.09	6.25%	0.480	0.631	No
10-70	0.05	3.47%	0.186	0.852	No
10-100	0.08	5.56%	0.235	0.814	No
40-70	-0.04	-2.61%	-0.294	0.769	No
40-100	-0.01	-0.65%	-0.245	0.807	No
70-100	0.03	2.01%	0.049	0.961	No

that while the differences were small and not significant, the largest differences were observed when going from the 10% profile to the others. The biggest increase of 6.25% in average score was observed when going from the 10% to the 40% profile. It can be concluded that an increase in ETHD speed results in a very small increase in user scores for the *Possibility To Act* component of immersion and presence when moving from the 10% speed profile to the others. The increase was not perceived as much when moving between the other speed profiles.

The coefficients from ordinal logistic regression (OLR) (summarised in Table E.3) indicated that the 40%, 70% and 100% speed profiles contributed to a small increase in user scores for *Possibility To Act*. The probabilities for each of the possible scores

Table E.3: OLR coefficients for 40%, 70% and 100% speed profiles for Possibility To Act (in relation to the 10% profile)

Speed Profile	OLR Coefficient
40%	0.24734
70%	0.09878
100%	0.12175

from this model is visualised in Figure E.3 where it can be seen that the 10% profile had slightly higher probabilities for the users to choose lower scores and the 40%, 70% and 100% speed profiles had slightly higher probabilities for users to choose higher scores, with the 40% profile having the highest probabilities.

Overall, the analysis indicates a small increase in user scores for the *Possibility To Act* component of Immersion and Presence as the ETHD speed increases.



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E.2 Immersion and Presence - Quality Of Interface

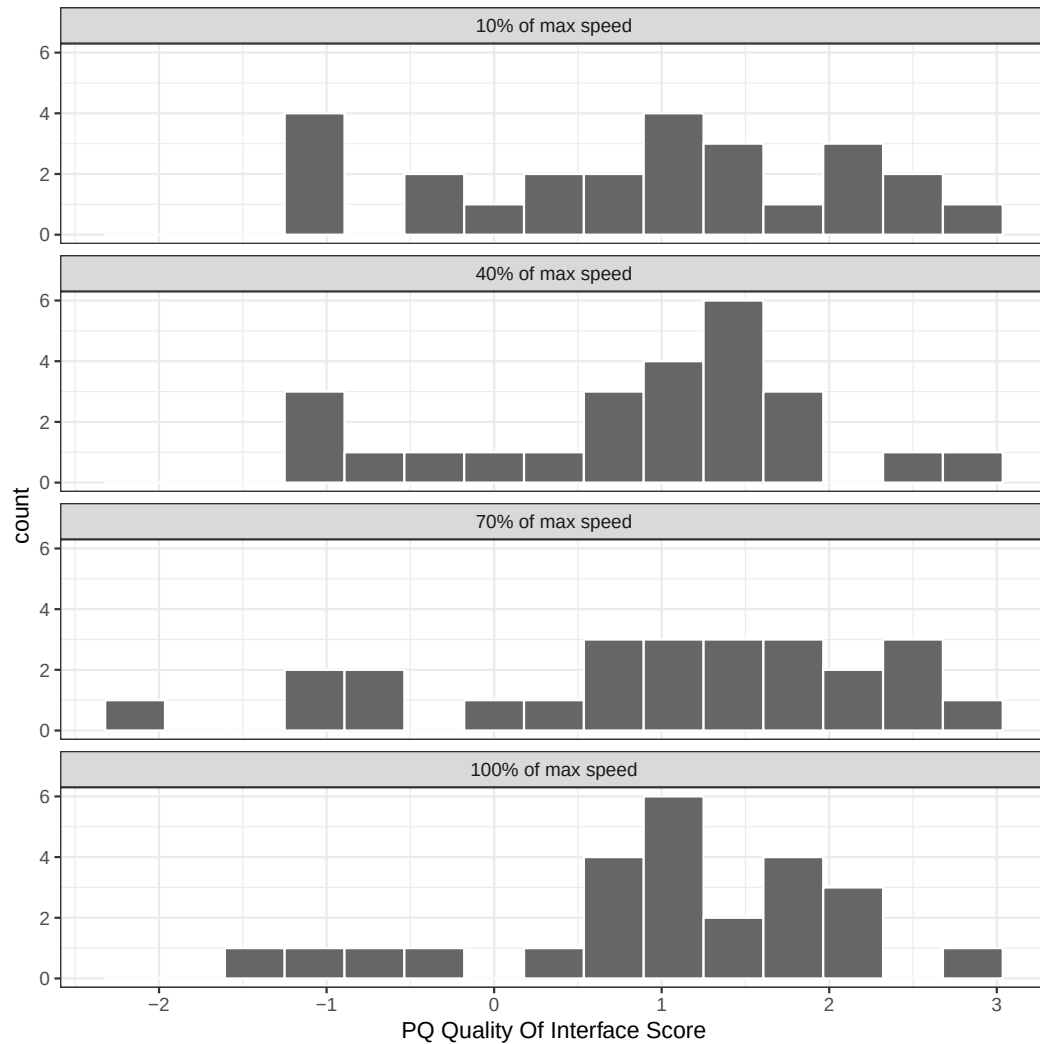


Figure E.4: Quality Of Interface score frequencies for each speed profile

The three questions for *Quality Of Interface* from the PQ resulted in 19 possible ordinal score outcomes within the range of -3 to +3, with an interval of 0.333 between values. These final score value frequencies are reported in Figure E.4 for each speed profile. Means and standard deviations are summarised in Table E.4. These score averages and data distributions are visualised in Figure E.5. The score averages for all speed profiles indicated positive sentiment in this scale. A slight increase in score was observed as the speed profile was increased.

The Kruskal-Wallis test was then done and resulted in $\chi^2 = 0.410$ and $p\text{-value} = 0.938$, indicating no significant differences in means. A result of $\eta^2 = -0.027$ indicated a small effect size. Results from Dunn's test (summarised in Table E.5) also indicated

Table E.4: Mean scores and standard deviation results for 10%, 40%, 70% and 100% ETHD speed profiles on Quality Of Interface

Speed Profile	Mean	Standard Deviation
10%	0.827	1.160
40%	0.827	1.030
70%	0.920	1.240
100%	0.960	0.997

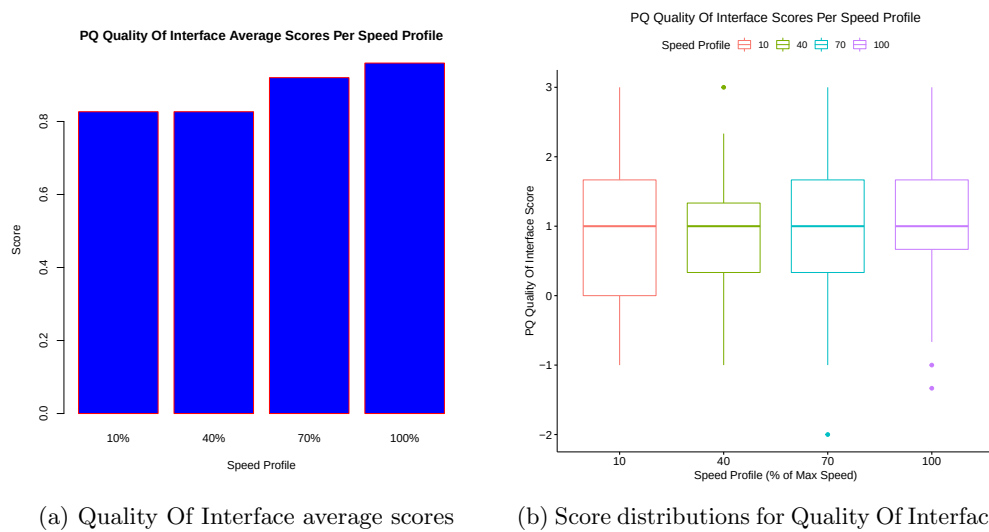


Figure E.5: Score averages and distributions for the Quality Of Interface from the PQ

no significant differences between speed profile pairs. It was noted that while the differences were small and not significant, the largest differences were observed when going from the 10% and 40% profiles to the 70% and 100% profiles. Moving from the 10% and 40% profiles to the 100% profile resulted in the largest change in average score of 16.08%. It can be concluded that an increase in ETHD speed results in a very small increase in user scores for the *Quality Of Interface* component of immersion and presence when moving from the 10% and 40% profiles to the 70% and 100% profiles.

The coefficients from ordinal logistic regression (summarised in Table E.6) indicated that the 70% and 100% speed profiles contributed to a small increase in user scores for *Quality Of Interface*. The 40% profile resulted in a negligible decrease in user scores. The probabilities for each of the possible scores from this model is visualised in Figure E.6. It can be seen that the 10% and 40% profiles had slightly higher

Table E.5: Multiple pairwise-comparison results from Dunn’s test for 10%, 40%, 70% and 100% ETHD speed profiles on Quality Of Interface

Test Pair	Mean Difference	Mean Difference %	z-statistic	p -value	Significantly Different?
10-40	0.00	0.00%	-0.0417	0.967	No
10-70	0.09	11.25%	0.4830	0.629	No
10-100	0.13	16.08%	0.3630	0.717	No
40-70	0.09	11.25%	0.5250	0.600	No
40-100	0.13	16.08%	0.4050	0.686	No
70-100	0.04	4.35%	-0.1200	0.904	No

Table E.6: OLR coefficients for 40%, 70% and 100% speed profiles for Quality Of Interface (in relation to the 10% profile)

Speed Profile	OLR Coefficient
40%	-0.00621
70%	0.25914
100%	0.18161

probabilities for the users to choose lower scores and the 70% and 100% speed profiles had slightly higher probabilities for users to choose higher scores, with the 70% profile having the highest probabilities.

Overall, the analysis indicated a small increase in user scores for the *Quality Of Interface* component of Immersion and Presence as the ETHD speed increased.

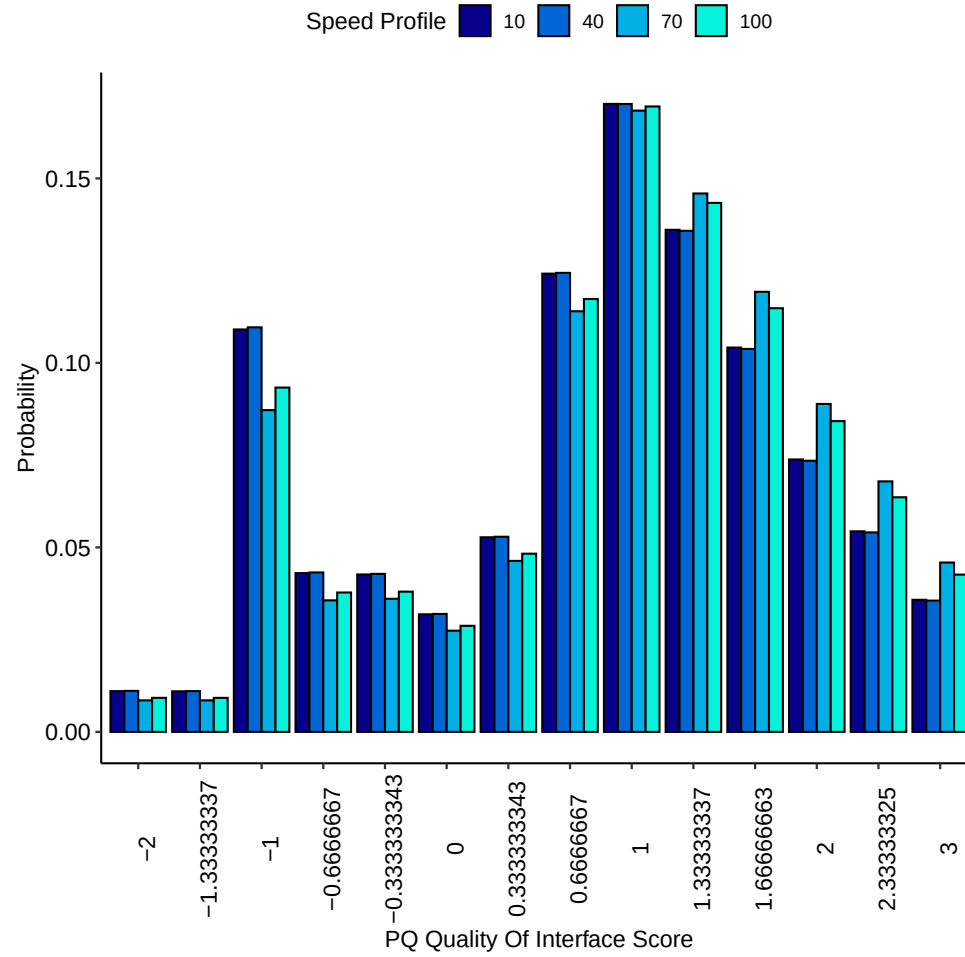


Figure E.6: Probabilities of Quality Of Interface average scores for each speed profile

E.3 User Experience - Attractiveness

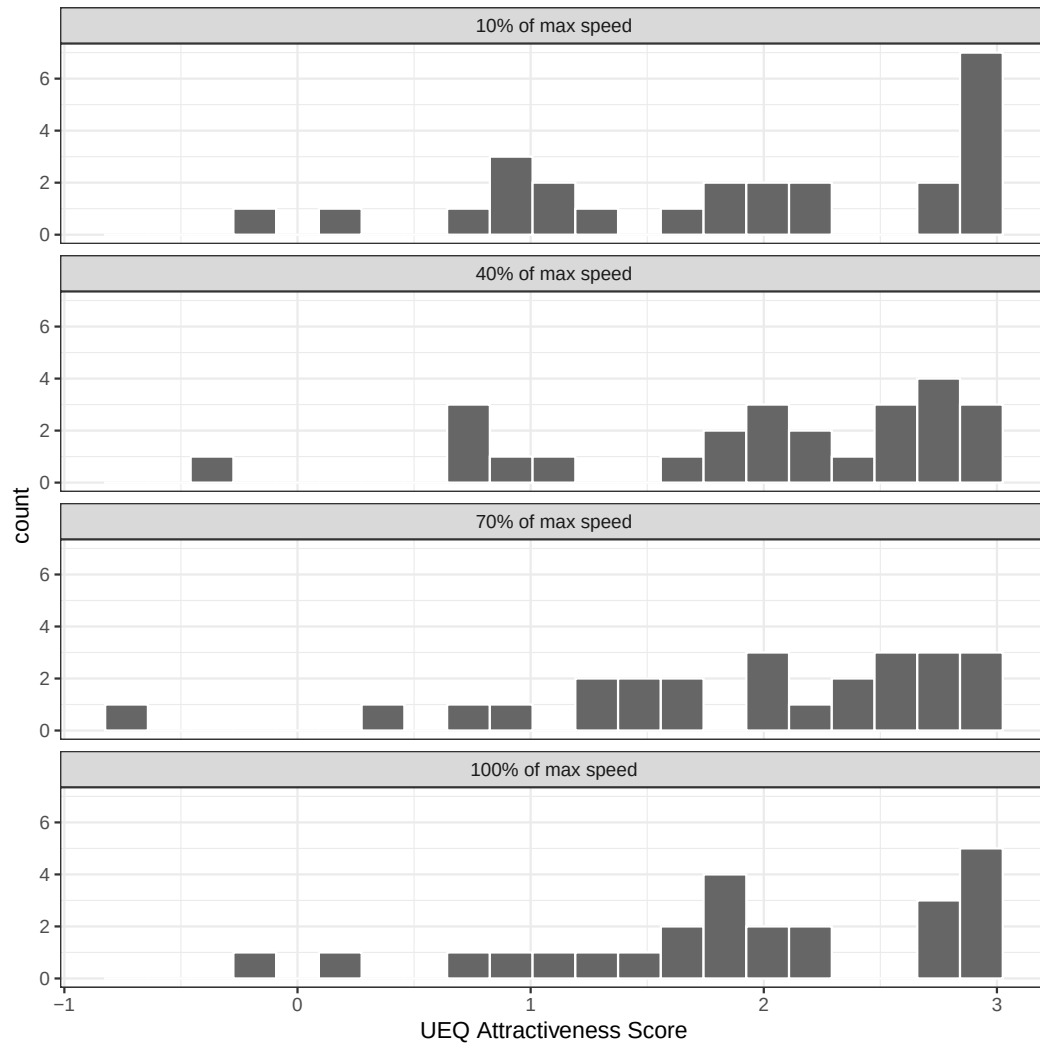


Figure E.7: Attractiveness score frequencies for each speed profile

The six questions for *Attractiveness* from the UEQ result in 37 possible ordinal score outcomes within the range of -3 to +3, with an interval of 0.166 between values. These final score value frequencies are reported in Figure E.7 for each speed profile. Means and standard deviations are summarised in Table E.7. These score averages and data distributions are visualised in Figure E.8. The score averages for all speed profiles were roughly the same, with the exception of the 40% profile having the highest average.

The Kruskal-Wallis test was then done and resulted in $\chi^2 = 0.0943$ and $p\text{-value} = 0.993$, indicating no significant differences in means. A result of $\eta^2 = -0.0303$ indicated a small effect size. Results from Dunn's test (summarised in Table E.8)

Table E.7: Mean scores and standard deviation results for 10%, 40%, 70% and 100% ETHD speed profiles on Attractiveness

Speed Profile	Mean	Standard Deviation
10%	1.90	0.974
40%	1.98	0.891
70%	1.92	0.912
100%	1.91	0.904

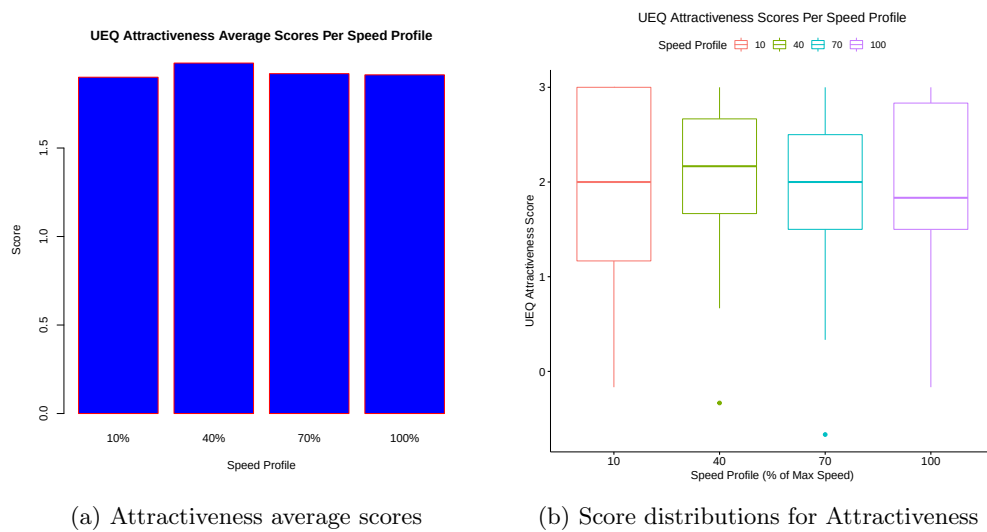


Figure E.8: Score averages and distributions for the Attractiveness from the UEQ

also indicated no significant differences between speed profile pairs. It was noted that while the differences were small and not significant, the largest differences were observed when going from the 10% profile to the others. The biggest increase of 4.21% in average score was observed when going from the 10% to the 40% profile. A result that was not expected was that the scores dropped slightly when moving from the 40% profile to the faster profiles. It can be concluded that an increase in ETHD speed results in a negligible increase in the *Attractiveness* component of UX when moving from the 10% speed profile to the others.

The coefficients from ordinal logistic regression (summarised in Table E.9) indicated that the 40% speed profile contributed to a very small increase in sentiment for *Attractiveness*, while the 70% and 100% profiles resulted in a very small decrease in user scores. The probabilities for each of the possible scores from this model is visualised in Figure E.9, where it can be seen that the all speed profiles had roughly the same probability for the users to choose any scores, with the exception of the

Table E.8: Multiple pairwise-comparison results from Dunn’s test for 10%, 40%, 70% and 100% ETHD speed profiles on Attractiveness

Test Pair	Mean Difference	Mean Difference %	z-statistic	p -value	Significantly Different?
10-40	0.08	4.21%	0.1910	0.849	No
10-70	0.02	1.05%	-0.0465	0.963	No
10-100	0.01	0.53%	-0.0955	0.924	No
40-70	-0.06	-3.03%	-0.2380	0.812	No
40-100	-0.07	-3.54%	-0.2860	0.775	No
70-100	-0.01	-0.52%	-0.0490	0.961	No

Table E.9: OLR coefficients for 40%, 70% and 100% speed profiles for Attractiveness (in relation to the 10% profile)

Speed Profile	OLR Coefficient
40%	0.09177
70%	-0.01998
100%	-0.04654

40% profile having slightly higher probabilities for users to choose the higher scores at the extreme end of the positive range.

Overall, the analysis indicated that an increase in ETHD speed did not have much effect on user scores for the *Attractiveness* component of UX.

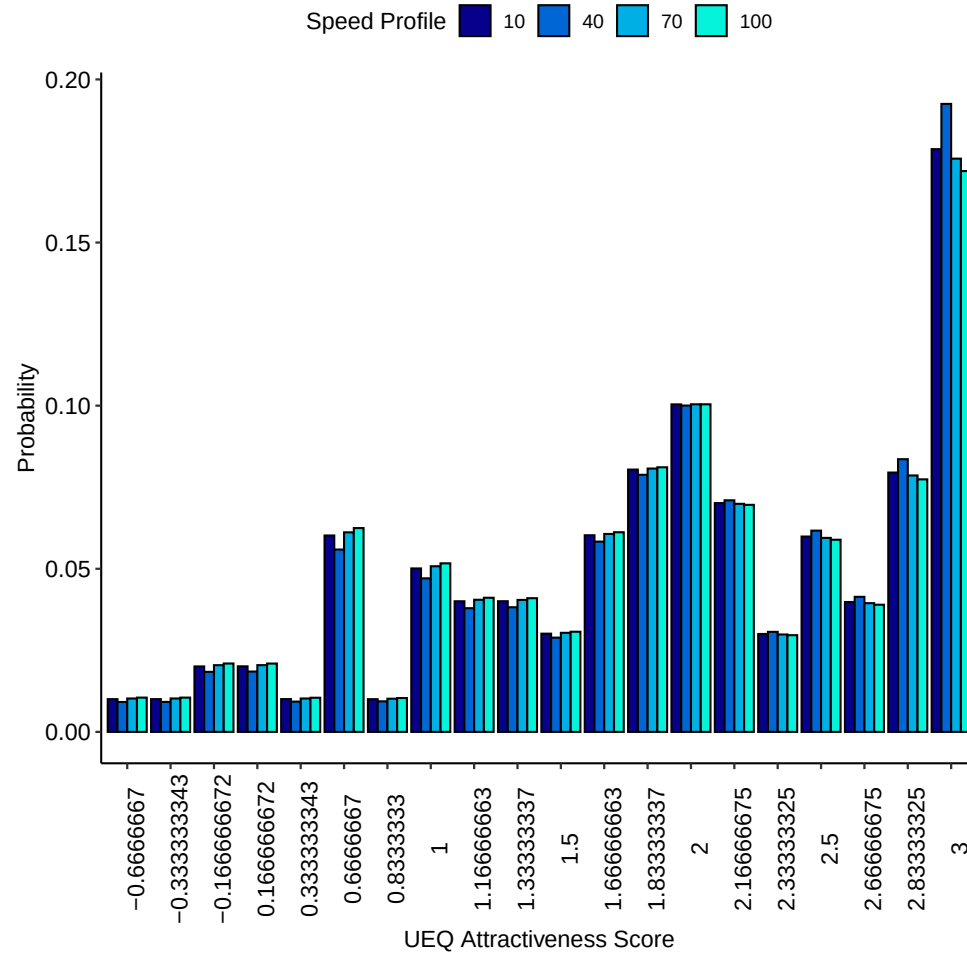


Figure E.9: Probabilities of Attractiveness average scores for each speed profile

E.4 User Experience - Efficiency

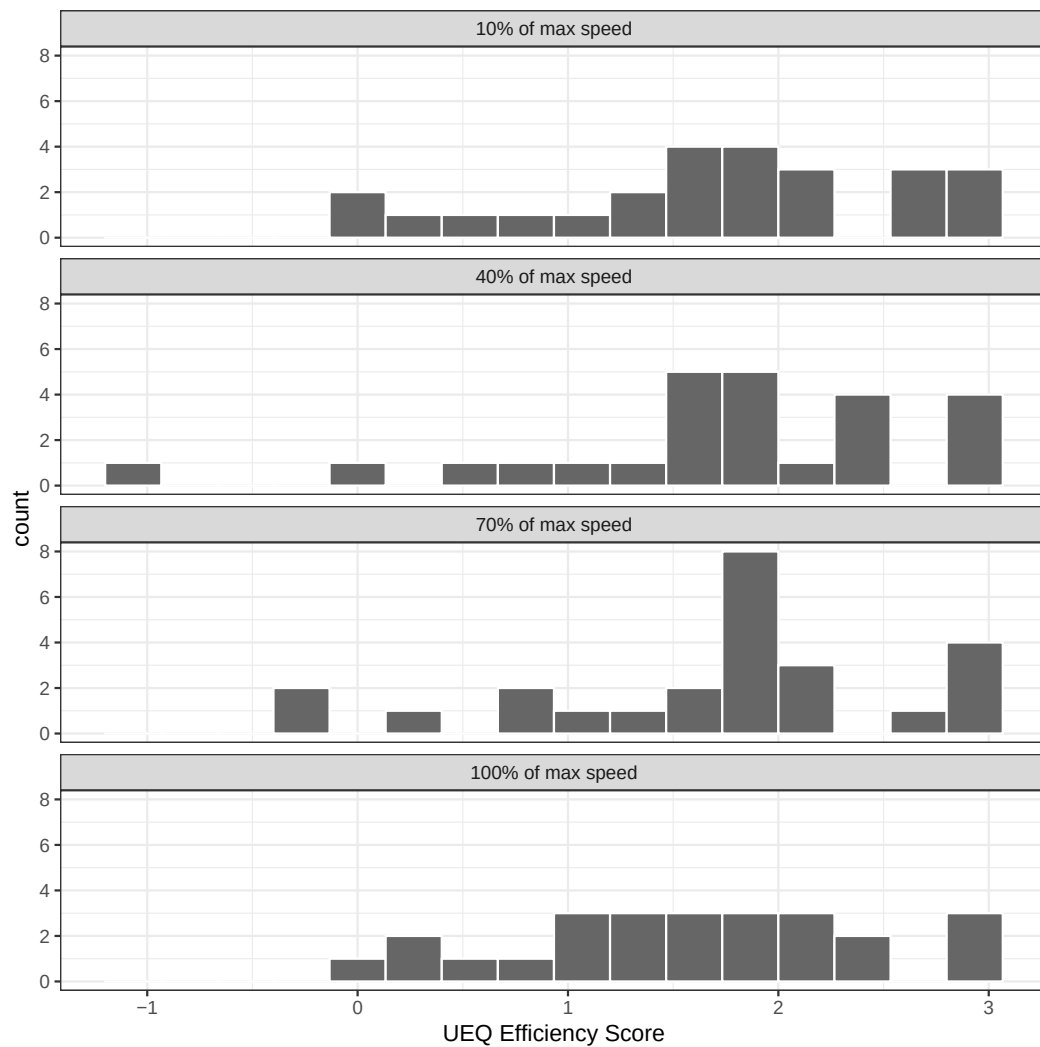


Figure E.10: Probabilities of Efficiency score frequencies for each speed profile

The four questions for *Efficiency* from the UEQ, when averaged with Equation 5.3, result in 25 possible ordinal score outcomes within the range of -3 to +3, with an interval of 0.25 between values. These final score value frequencies are reported in Figure E.10 for each speed profile. Means and standard deviations are summarised in Table E.10. These score averages and data distributions are visualised in Figure E.11. The score averages for all speed profiles indicated positive sentiment in this scale. A slight increase in score was observed as the speed profile was increased from the 10% to the 40% profile, but then surprisingly dropped when moving to the 70% and 100% profiles.

The Kruskal-Wallis test was then done and resulted in $\chi^2 = 1.05$ and $p\text{-value} = 0.79$,

Table E.10: Mean scores and standard deviation results for 10%, 40%, 70% and 100% ETHD speed profiles on Efficiency

Speed Profile	Mean	Standard Deviation
10%	1.68	0.926
40%	1.75	0.984
70%	1.72	0.945
100%	1.57	0.880

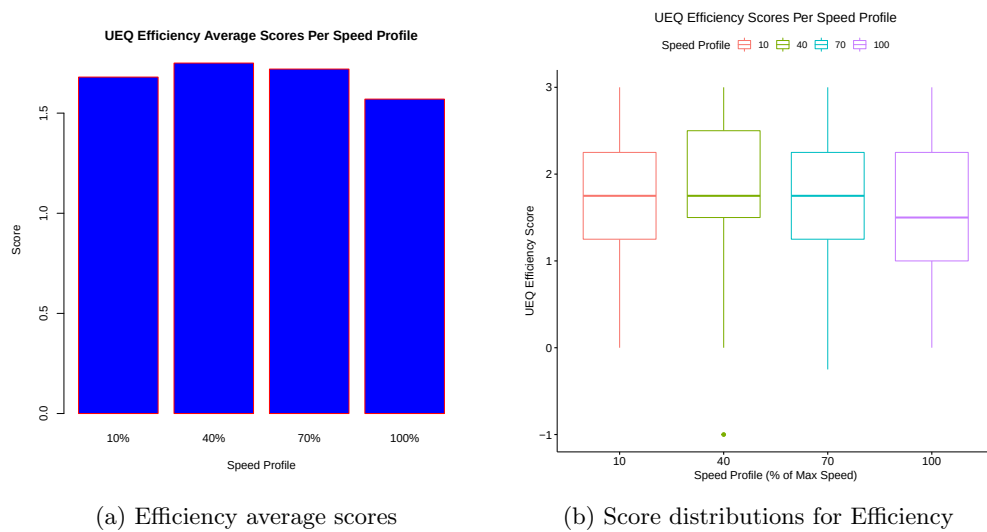


Figure E.11: Score averages and distributions for the Efficiency from the UEQ

indicating no significant differences in means. A result of $\eta^2 = -0.0204$ indicated a small effect size. Results from Dunn's test (summarised in Table E.11) also indicated no significant differences between speed profile pairs. It was noted that while the differences were small and not significant, a small increase of 2.38%-4.17% was observed when going from the 10% profile to the 40% and 70% profile. However, the *Efficiency* scores appeared to drop for certain cases unexpectedly, most notably a drop of 10.29% in score when moving from the 40% to 100% profile. These results were inconclusive and could have been caused by users only being exposed to each profile once in a random order. Repeated exposure to all speed profiles in future studies might be able to give more conclusive results on *Efficiency*.

The coefficients from ordinal logistic regression (summarised in Table E.12) indicated that the 40% and 70% speed profiles contributed to a small increase in user scores for *Efficiency* while the 100% profile resulted in a small decrease in user scores. The probabilities for each of the possible scores arising from this model is visualised in

Table E.11: Multiple pairwise-comparison results from Dunn’s test for 10%, 40%, 70% and 100% ETHD speed profiles on Efficiency

Test Pair	Mean Difference	Mean Difference %	z-statistic	p -value	Significantly Different?
10-40	0.07	4.17%	0.460	0.645	No
10-70	0.04	2.38%	0.316	0.752	No
10-100	-0.11	-6.55%	-0.483	0.629	No
40-70	-0.03	-1.71%	-0.145	0.885	No
40-100	-0.18	-10.29%	-0.943	0.346	No
70-100	-0.15	-8.72%	-0.798	0.425	No

Table E.12: OLR coefficients for 40%, 70% and 100% speed profiles for Efficiency (in relation to the 10% profile)

Speed Profile	OLR Coefficient
40%	0.2296
70%	0.1590
100%	-0.2395

Figure E.12 where it can be seen that, unexpectedly, both 10% and 100% profiles had the highest probability for lower scores. The 40% and 70% profiles had higher probabilities for users to choose higher scores.

Overall, the analysis indicated that an increase in ETHD speed did result in a small increase on user scores for the *Efficiency* component of UX. However, the highest speed profile of 100% had unexpectedly lower scores than the others, and further studies would need to be done to verify if this outcome persists or was merely an anomaly arising from participants being only exposed to each speed profile once.

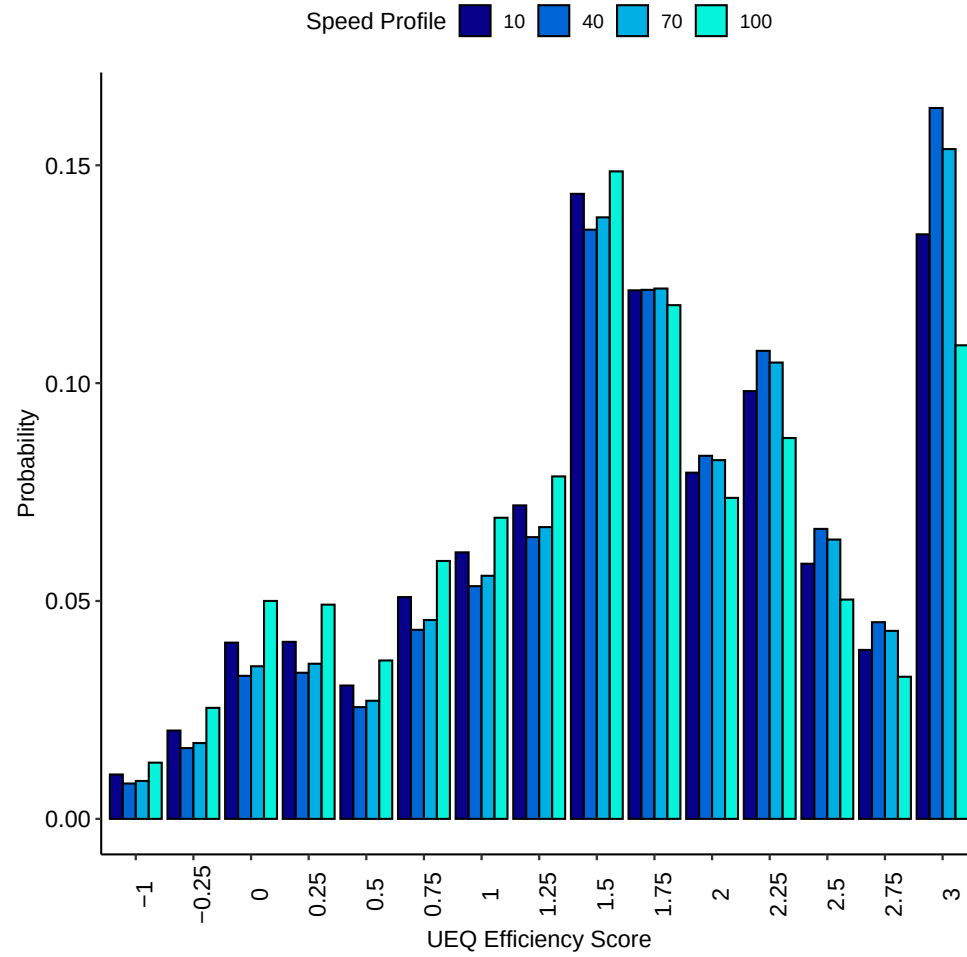


Figure E.12: Probabilities of Efficiency average scores for each speed profile

E.5 User Experience - Dependability

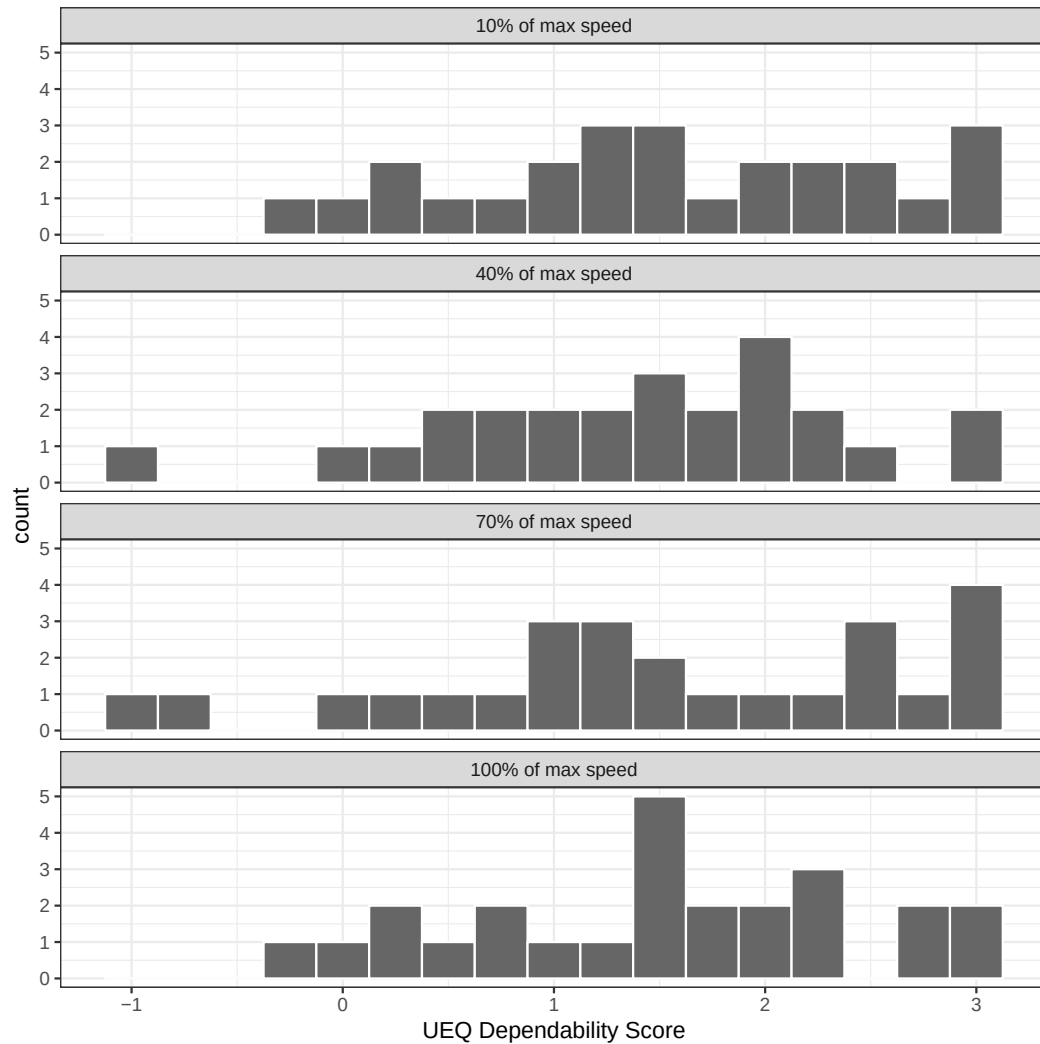


Figure E.13: Dependability score frequencies for each speed profile

The four questions for *Dependability* from the UEQ, when averaged with Equation 5.3, result in 25 possible ordinal score outcomes within the range of -3 to +3, with an interval of 0.25 between values. These final score value frequencies are reported in Figure E.13 for each speed profile. Means and standard deviations are summarised in Table E.13. These score averages and data distributions are visualised in Figure E.14. The score averages for all speed profiles indicated positive sentiment in this scale. A slight increase in score was observed as the speed profile was increased for certain cases, and, unexpectedly, there were also some large dips in score.

The Kruskal-Wallis test was then done and resulted in $\chi^2 = 0.237$ and p -value = 0.971, indicating no significant differences in means. A result of $\eta^2 = -0.0288$

Table E.13: Mean scores and standard deviation results for 10%, 40%, 70% and 100% ETHD speed profiles on Dependability

Speed Profile	Mean	Standard Deviation
10%	1.55	0.971
40%	1.41	0.943
70%	1.51	1.160
100%	1.51	0.931

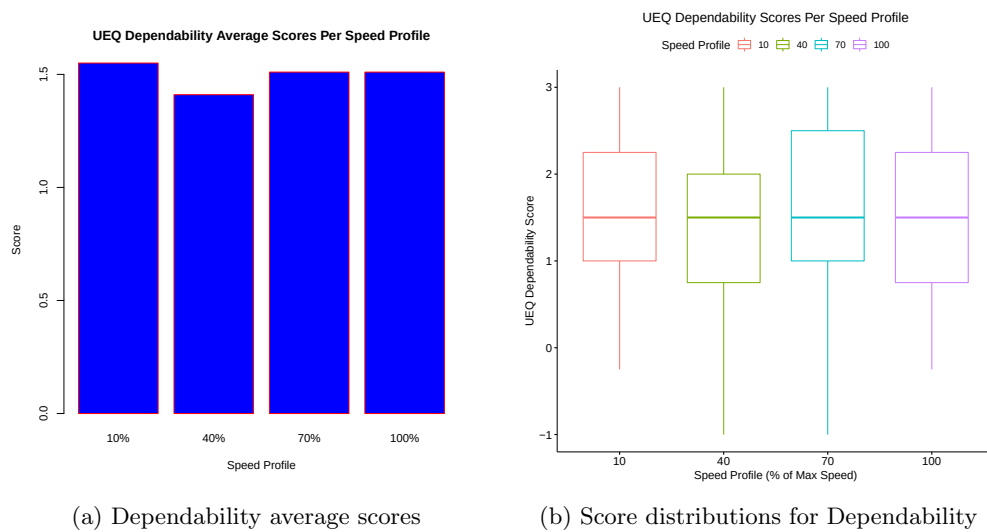


Figure E.14: Score averages and distributions for the Dependability from the UEQ

indicated a small effect size. Results from Dunn's test (summarised in Table E.14) also indicated no significant differences between speed profile pairs. It was noted that all differences were small and not significant. For average *Dependability* scores, the only increase observed was a 7.09% increase from the 40% profile to the 70% and 100% profiles. The majority of differences were a decrease in average score from the 10% to the other speed profiles. The biggest decrease of 9.03% was observed when going from the 10% to the 40% profile. These results are inconclusive and could have been caused by users only being exposed to each profile once in a random order. Repeated exposure to all speed profiles in future studies might be able to give more conclusive results on *Dependability*.

The coefficients from ordinal logistic regression (summarised in Table E.15) indicated that the 40% and 100% speed profiles contributed to a small decrease in user scores for *Dependability*, while the 70% profile resulted in a very small increase in user scores. The probabilities for each of the possible scores from this model is visualised

Table E.14: Multiple pairwise-comparison results from Dunn’s test for 10%, 40%, 70% and 100% ETHD speed profiles on Dependability

Test Pair	Mean Difference	Mean Difference %	z-statistic	p -value	Significantly Different?
10-40	-0.14	-9.03%	-0.4130	0.679	No
10-70	-0.04	-2.58%	0.0147	0.988	No
10-100	-0.04	-2.58%	-0.1100	0.912	No
40-70	0.10	7.09%	0.4280	0.669	No
40-100	0.10	7.09%	0.3030	0.762	No
70-100	0.00	0.00%	-0.1205	0.901	No

Table E.15: OLR coefficients for 40%, 70% and 100% speed profiles for Dependability (in relation to the 10% profile)

Speed Profile	OLR Coefficient
40%	-0.19617
70%	0.01454
100%	-0.05552

in Figure E.15, where it can be seen that, unexpectedly, all speed profiles had roughly the same probabilities for users to choose any score. It was only the 40% profile that had a slightly higher probability for users to choose lower scores and a lower probability for users to choose higher scores.

Overall, the analysis indicated that an increase in ETHD speed mostly resulted in a small increase in user scores for the *Dependability* component of UX. Similar to the results for *Efficiency*, further studies would need to be done to verify if this outcome persists or was just an anomaly arising from participants being only exposed to each speed profile once.

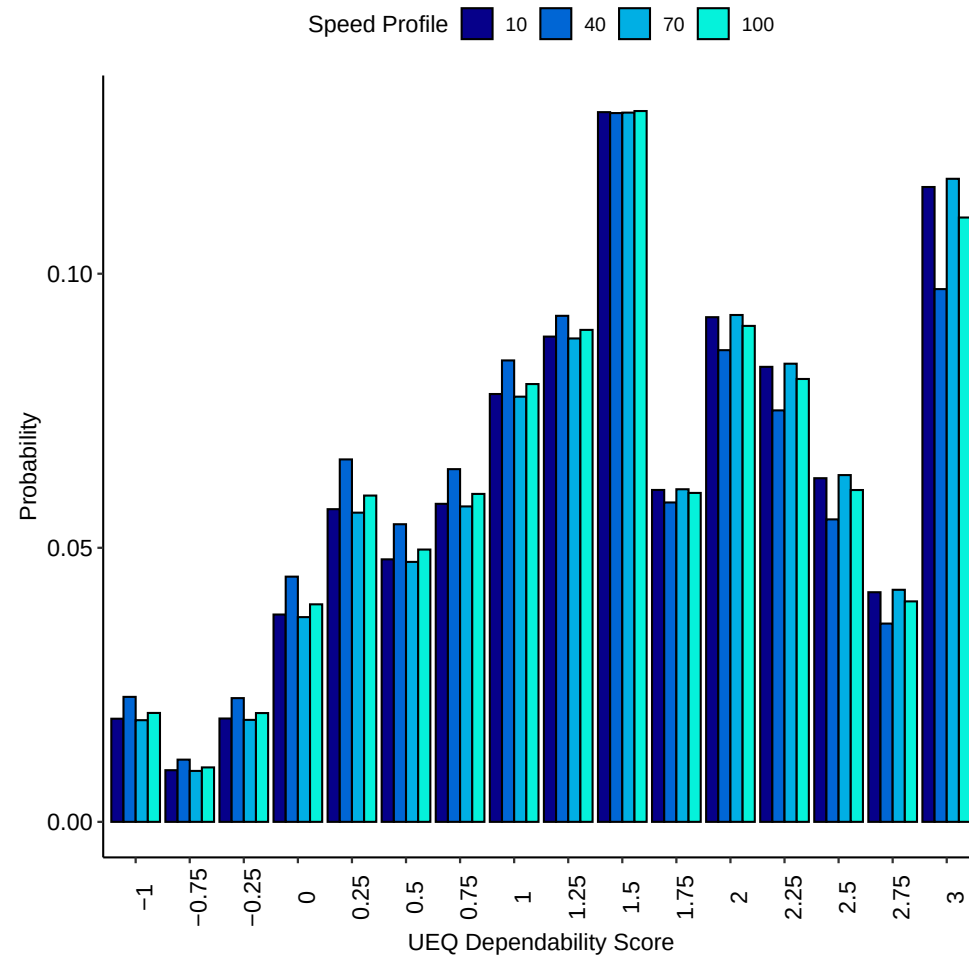


Figure E.15: Probabilities of Dependability average scores for each speed profile

E.6 Game Performance - Total Aliens Hit

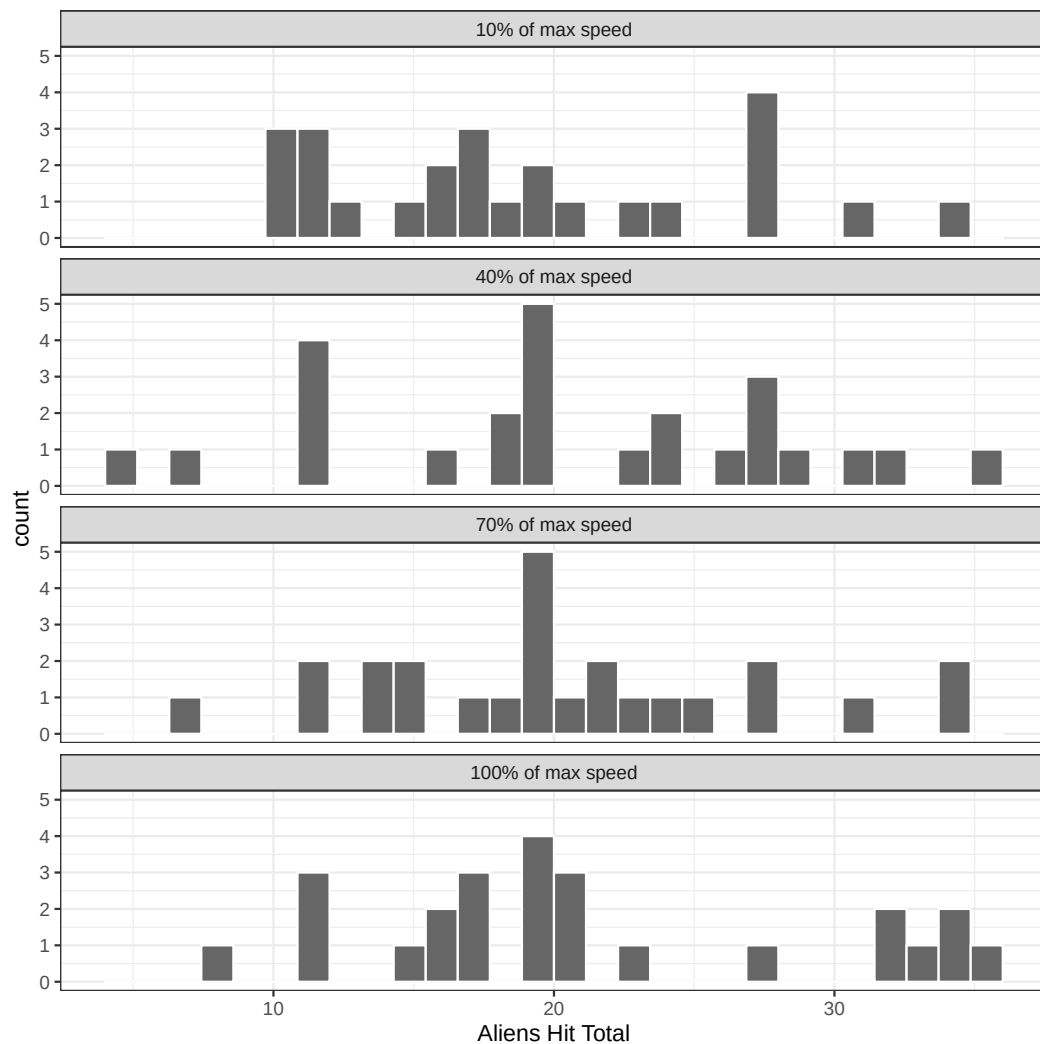


Figure E.16: Total Aliens Hit score frequencies for each speed profile

For the overall performance of players in the game, scores for *Total Aliens Hit* were recorded as the total number of aliens hit before the timer ran out. For this category, 36 aliens were available to be shot down in one round. After the training, skilled users would be able to employ the Normal, Double, Laser and Big Shots to shoot down as many aliens as possible in a round. This resulted in 36 possible ordinal integer score outcomes lying within the range of 1 to 36. These final score value frequencies are reported in Figure E.16 for each speed profile. Means and standard deviations are summarised in Table E.16. These score averages and data distributions are visualised in Figure E.17. A small increase in average score was observed as the speed profile was increased. Only two different participants were able to shoot down all 36 aliens within the 45 second time limit. This event happened once for each

Table E.16: Mean scores and standard deviation results for 10%, 40%, 70% and 100% ETHD speed profiles on Total Aliens Hit

Speed Profile	Mean	Standard Deviation
10%	19.1	7.10
40%	20.7	8.00
70%	20.4	6.92
100%	21.3	8.12

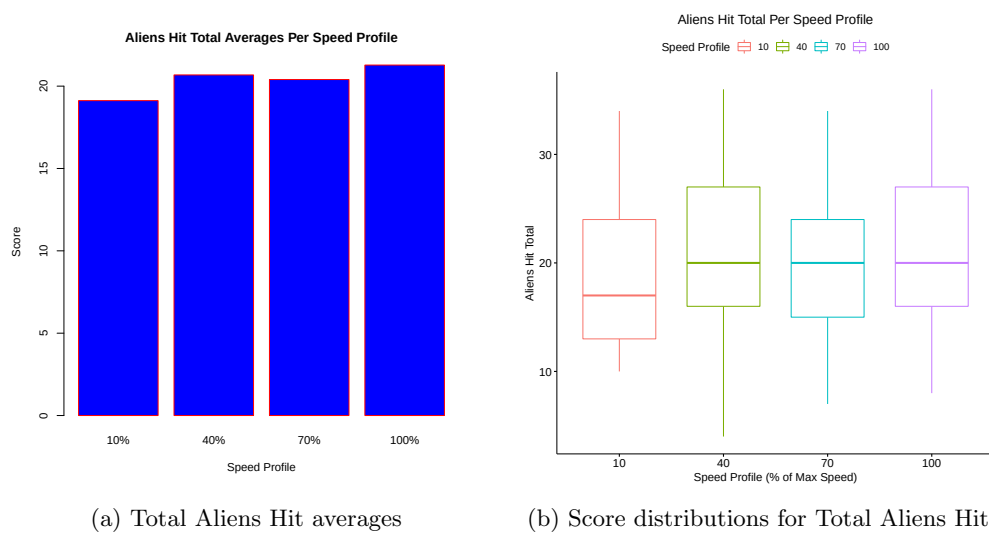


Figure E.17: Score averages and distributions for Total Aliens Hit

of these participants, one for the 40% profile and the other occurred on the 100% profile.

The Kruskal-Wallis test was then done and resulted in $\chi^2 = 1.25$ and $p\text{-value} = 0.741$, indicating no significant differences in means. A result of $\eta^2 = -0.0182$ indicated a small effect size. Results from Dunn's test (summarised in Table E.17) also indicated no significant differences between speed profile pairs. It was noted that all differences were small and not significant. For *Total Aliens Hit*, there was a clear indication that the average user score increased with increasing speed profile. This was especially noticeable when moving from the 10% profile to the other speed profiles. In particular, going from the 10% profile to the 100% profile yielded the greatest increase of 11.52%.

The coefficients from ordinal logistic regression (summarised in Table E.18) indicated that the 40%, 70% and 100% speed profiles all contributed to a small increase in scores for *Total Aliens Hit*. The probabilities for each of the possible scores from this

Table E.17: Multiple pairwise-comparison results from Dunn’s test for 10%, 40%, 70% and 100% ETHD speed profiles on Total Aliens Hit

Test Pair	Mean Difference	Mean Difference %	z-statistic	p -value	Significantly Different?
10-40	1.56	8.38%	0.9760	0.329	No
10-70	1.28	6.81%	0.7400	0.460	No
10-100	2.16	11.52%	0.9500	0.342	No
40-70	-0.28	-1.45%	-0.2370	0.813	No
40-100	0.60	2.90%	-0.0269	0.979	No
70-100	0.88	4.41%	0.2100	0.834	No

Table E.18: OLR coefficients for 40%, 70% and 100% speed profiles for Total Aliens Hit (in relation to the 10% profile)

Speed Profile	OLR Coefficient
40%	0.4928
70%	0.3715
100%	0.4813

model is visualised in Figure E.18 where it can be clearly seen that the 10% profile had much higher probabilities for users to get lower scores. The 40%, 70% and 100% profiles all had much higher, and roughly equal, probabilities for users to get higher scores.

Overall, the analysis indicated that an increase in ETHD speed resulted in a small increase in scores for *Total Aliens Hit*.

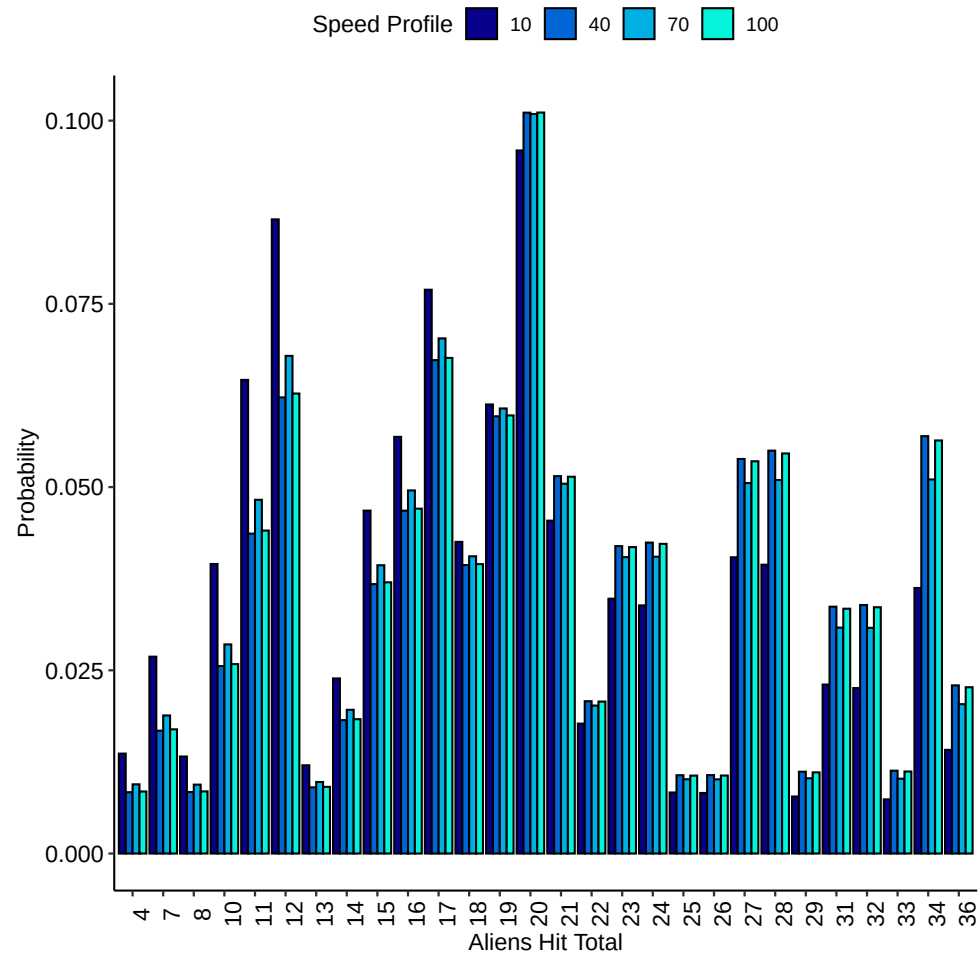


Figure E.18: Probabilities of Total Aliens Hit average scores for each speed profile

E.7 Game Performance - Aliens Hit by Normal and Double Shots

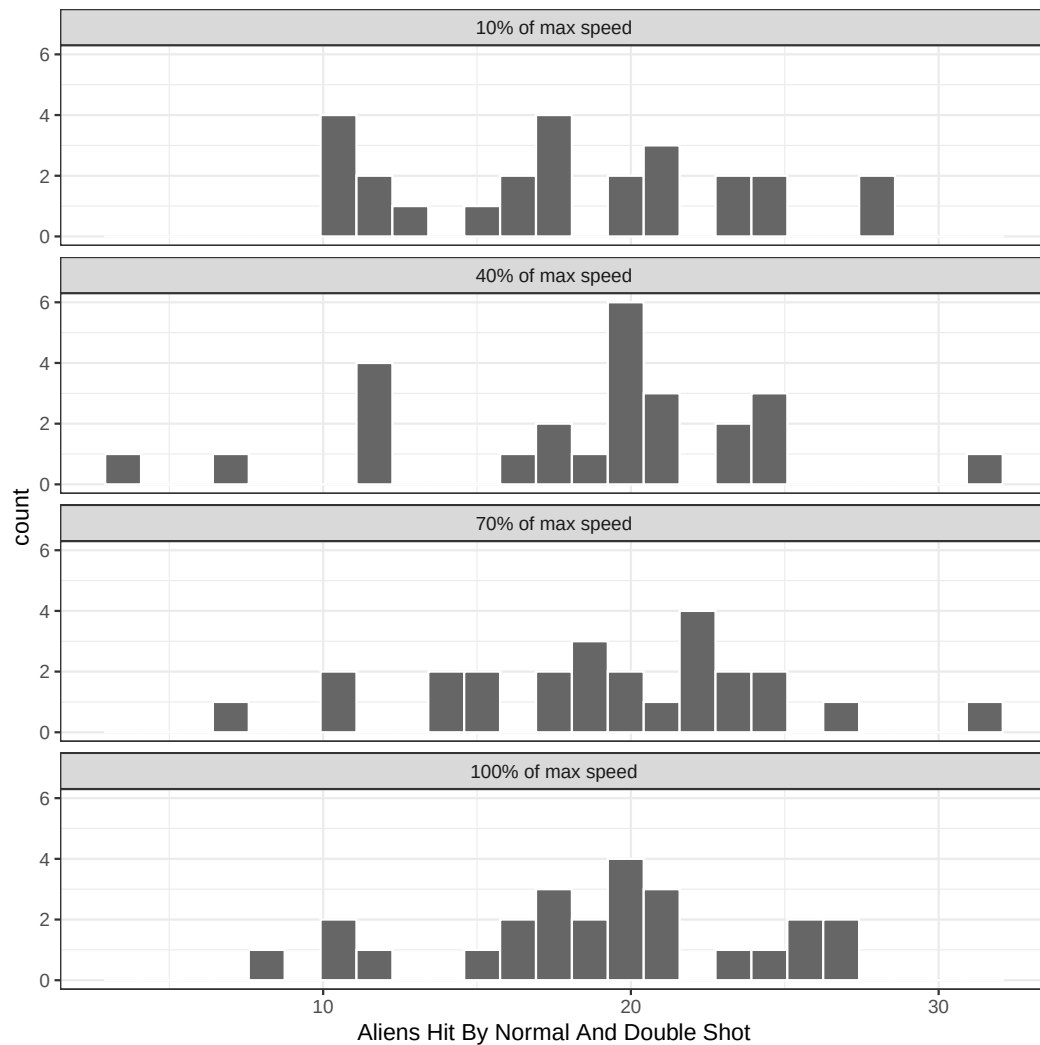


Figure E.19: Aliens Hit by Normal and Double Shots score frequencies for each speed profile

The scores for *Aliens Hit by Normal and Double Shots* were a subset of *Total Aliens Hit*. For this category, the number of aliens shot down by the standard Normal and Double Shots were analysed. The minimum number of aliens shot down in this category was 4 and the maximum was 32 giving a total of 29 possible ordinal integer score outcomes. These final score value frequencies are reported in Figure E.19 for each speed profile. Means and standard deviations are summarised in Table E.19. These score averages and data distributions are visualised in Figure E.20. As was observed for *Total Aliens Hit*, the score averages for *Aliens Hit by Normal and Double*

Table E.19: Mean scores and standard deviation results for 10%, 40%, 70% and 100% ETHD speed profiles on Aliens Hit by Normal and Double Shots

Speed Profile	Mean	Standard Deviation
10%	18.0	5.56
40%	18.5	5.95
70%	19.3	5.50
100%	19.0	5.11

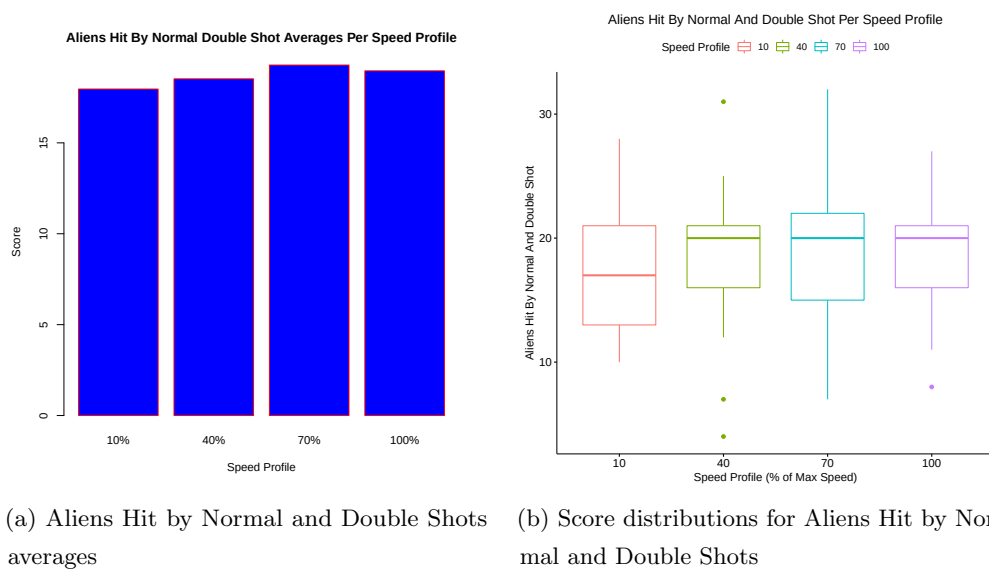


Figure E.20: Score averages and distributions for Aliens Hit by Normal and Double Shots

Shots displayed a small increase in average score as the speed profile was increased. The higher scores observed towards the maximum possible score of 36 in the parent category were most likely due to the time pressure causing users to forget or neglect the fact that the Laser and Big Shots were available to make the game easier, after reaching the milestone of 20 aliens shot down.

The Kruskal-Wallis test was then done and resulted in $\chi^2 = 0.817$ and p -value = 0.845, indicating no significant differences in means. A result of $\eta^2 = -0.0227$ indicated a small effect size. Results from Dunn's test (summarised in Table E.20) also indicated no significant differences between speed profile pairs. It was noted that all differences were small and not significant. For *Aliens Hit by Normal and Double Shots* there was again a clear indication that the average user score increased with increasing speed profile. This was especially noticeable when moving from the

Table E.20: Multiple pairwise-comparison results from Dunn's test for 10%, 40%, 70% and 100% ETHD speed profiles on Aliens Hit by Normal and Double Shots

Test Pair	Mean Difference	Mean Difference %	z-statistic	<i>p</i> -value	Significantly Different?
10-40	0.56	2.78%	0.5990	0.549	No
10-70	1.32	7.22%	0.8680	0.386	No
10-100	1.00	5.56%	0.6260	0.532	No
40-70	0.76	4.32%	0.2690	0.788	No
40-100	0.44	2.70%	0.0269	0.979	No
70-100	-0.32	-1.55%	-0.2420	0.809	No

10% profile to the other speed profiles. In particular, going from the 10% profile to the 70% profile yielded the greatest increase of 7.22%, which was observed as a small effect size. In addition, Figure E.21 shows that players were able to achieve above 92% success rates with regards to shooting down at least 10 aliens and achieving the Double Shot upgrade for all speed profiles. Unexpectedly, a 100% success rate was observed for the 10% profile, possibly due to participants using the alien motion to their advantage to compensate for the slow ETHD speed.

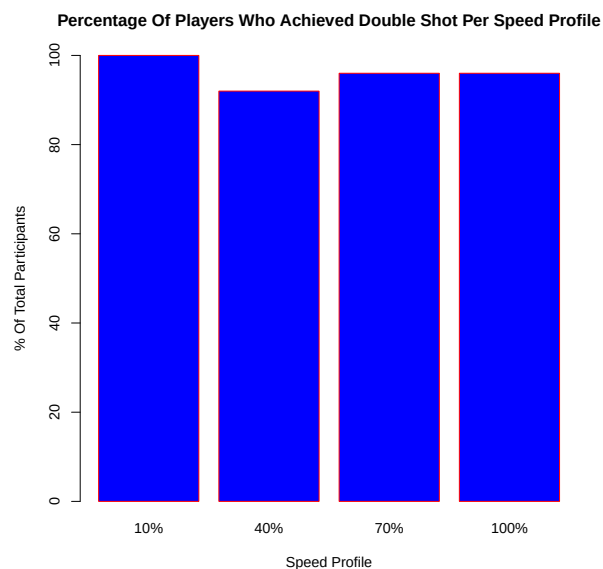


Figure E.21: The percentage of players who were able to achieve the Double Shot upgrade after 10 aliens were shot down.

Table E.21: OLR coefficients for 40%, 70% and 100% speed profiles for Aliens Hit by Normal and Double Shots (in relation to the 10% profile)

Speed Profile	OLR Coefficient
40%	0.3145
70%	0.4471
100%	0.3258

The coefficients from ordinal logistic regression (summarised in Table E.21) indicated that the 40%, 70% and 100% speed profiles all contributed to a small increase in scores for *Aliens Hit by Normal and Double Shots*. The probabilities for each of the possible scores from this model is visualised in Figure E.22 where it can be clearly seen that, as for the *Total Aliens Hit* parent category, the 10% profile had higher probabilities for users to get lower scores and the 40%, 70% and 100% profiles all had higher, and roughly equal, probabilities for users to get higher scores.

Overall, the analysis indicated that an increase in ETHD speed resulted in a small increase in scores for *Aliens Hit by Normal and Double Shots*.

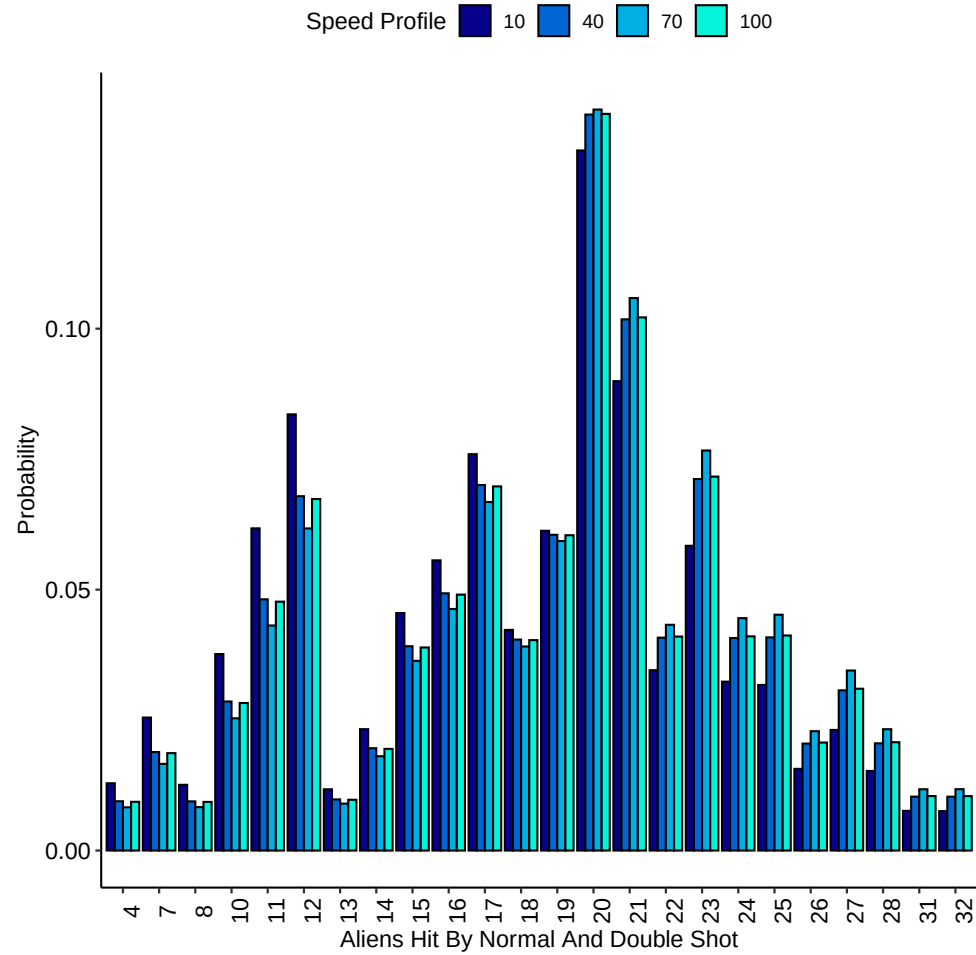


Figure E.22: Probabilities of Aliens Hit by Normal and Double Shots average scores for each speed profile

E.8 Game Performance - Aliens Hit by Laser and Big Shots

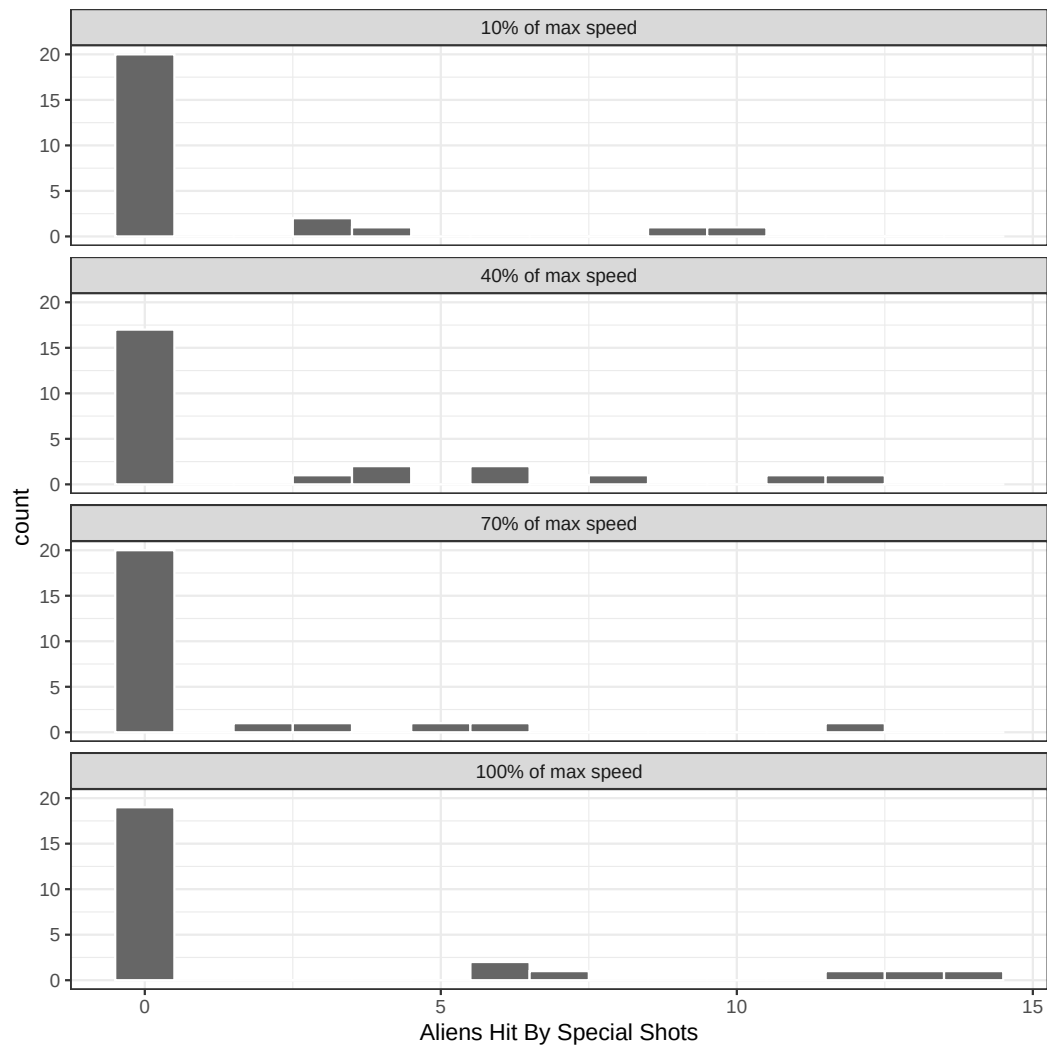


Figure E.23: Aliens Hit by Laser and Big Shots score frequencies for each speed profile

The scores for *Aliens Hit by Laser and Big Shots* were a subset of *Total Aliens Hit*. For this category, the number of aliens shot down by the special Laser and Big Shots were analysed. The minimum number of aliens shot down in this category was 0 and the maximum was 14, giving a total of 15 possible ordinal integer score outcomes. These final score value frequencies are reported in Figure E.23 for each speed profile. Means and standard deviations are summarised in Table E.22. These score averages and data distributions are visualised in Figure E.24. The score averages for *Aliens Hit by Laser and Big Shots* displayed a small increase in average score as the speed

Table E.22: Mean scores and standard deviation results for 10%, 40%, 70% and 100% ETHD speed profiles on Aliens Hit by Laser and Big Shots

Speed Profile	Mean	Standard Deviation
10%	1.16	2.75
40%	2.16	3.68
70%	1.12	2.79
100%	2.32	4.54

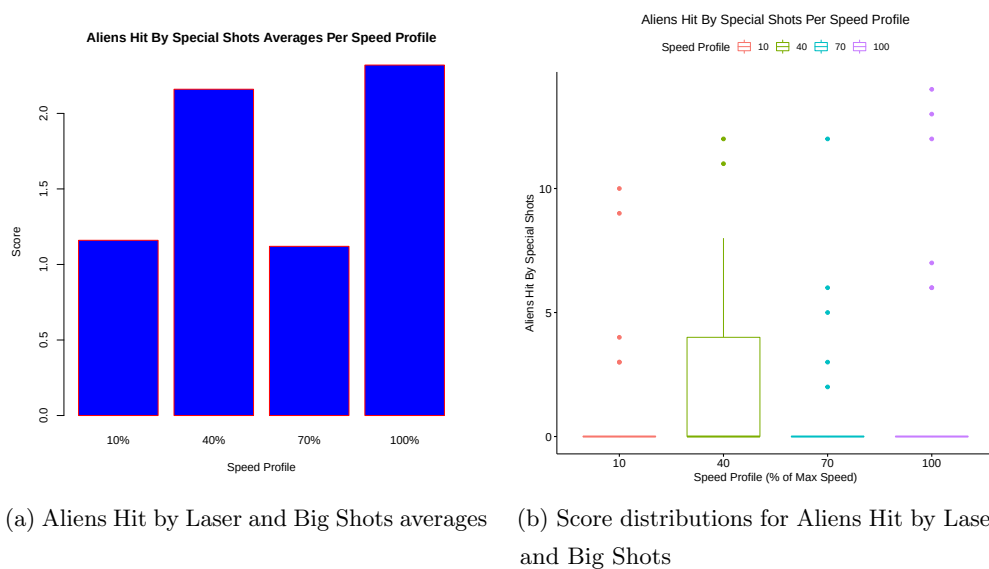


Figure E.24: Score averages and distributions for Aliens Hit by Laser and Big Shots

profile was increased, when moving from the 10% to the 40% and 100% profile, but for the 70% profile, the average score was actually lower than that of the 10% profile. However, this represented an average difference of just one alien less. Participants who achieved the higher scores in this category took the time to master the game using all possible offensive abilities offered to the player. The two participants who were able to clear out all aliens in the round both shot down a total of 12 aliens with these special shots.

The Kruskal-Wallis test was then done and resulted in $\chi^2 = 1.60$ and $p\text{-value} = 0.659$, indicating no significant differences in means. A result of $\eta^2 = -0.0146$ indicated a small effect size. Results from Dunn's test (summarised in Table E.23) also indicated no significant differences between speed profile pairs. It was noted that all differences were small and not significant. For *Aliens Hit by Laser and Big Shots*, the results were varied. Players especially did well by shooting down more aliens in the 100%

Table E.23: Multiple pairwise-comparison results from Dunn's test for 10%, 40%, 70% and 100% ETHD speed profiles on Aliens Hit by Laser and Big Shots

Test Pair	Mean Difference	Mean Difference %	z-statistic	<i>p</i> -value	Significantly Different?
10-40	1.00	86.21%	1.0500	0.295	No
10-70	-0.04	-3.45%	-0.0163	0.987	No
10-100	1.16	100.00%	0.6220	0.534	No
40-70	-1.04	-48.15%	-1.0600	0.287	No
40-100	0.16	7.41%	-0.4260	0.670	No
70-100	1.20	107.14%	0.6380	0.524	No

speed profile, but there was no noticeable increasing pattern, as the 40% and 100% profiles were almost double the scores seen for the 10% and 70% profiles. However, this result was very close, as it equated to just one more alien hit for the higher average scores. In addition, Figure E.25 shows that players were able to achieve 44%-60% success rates with regards to shooting down at least 20 aliens and achieving the Laser and Big Shot upgrades. The highest success rate for this achievement was for the 40% profile where a 60% success rate was noted.

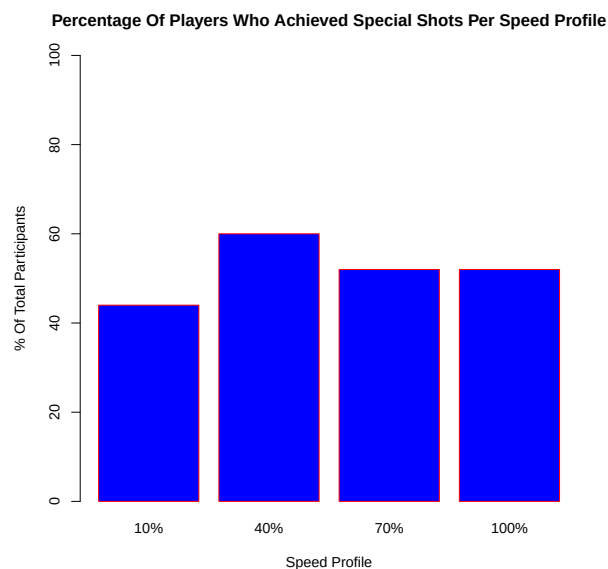


Figure E.25: The percentage of players who were able to achieve the Laser and Big Shot upgrades after 20 aliens were shot down.

Table E.24: OLR coefficients for 40%, 70% and 100% speed profiles for Aliens Hit by Laser and Big Shots (in relation to the 10% profile)

Speed Profile	OLR Coefficient
40%	0.65507
70%	-0.01046
100%	0.43182

The coefficients from ordinal logistic regression (summarised in Table E.24) indicated that the 40% and 100% speed profiles contributed to a small increase in scores for *Aliens Hit by Laser and Big Shots*. The 70% profile resulted in a very small decrease in user scores, but this was most likely an anomaly that could also be shown to have a positive coefficient with a larger sample size. The probabilities for each of the possible scores from this model is visualised in Figure E.26, where it can be clearly seen that most participants either did not achieve the Laser and Big Shots or forgot that these abilities were available. Across all speed profiles, the probabilities were roughly the same, with the highest probabilities (70%-80%) being observed for not hitting any aliens with the special shots.

Overall, the analysis indicated that an increase in ETHD speed resulted in a small increase in scores for *Aliens Hit by Laser and Big Shots*. The large drop for the 70% profile was most likely an anomaly that could be corrected by repeating the experiment with a larger sample size.

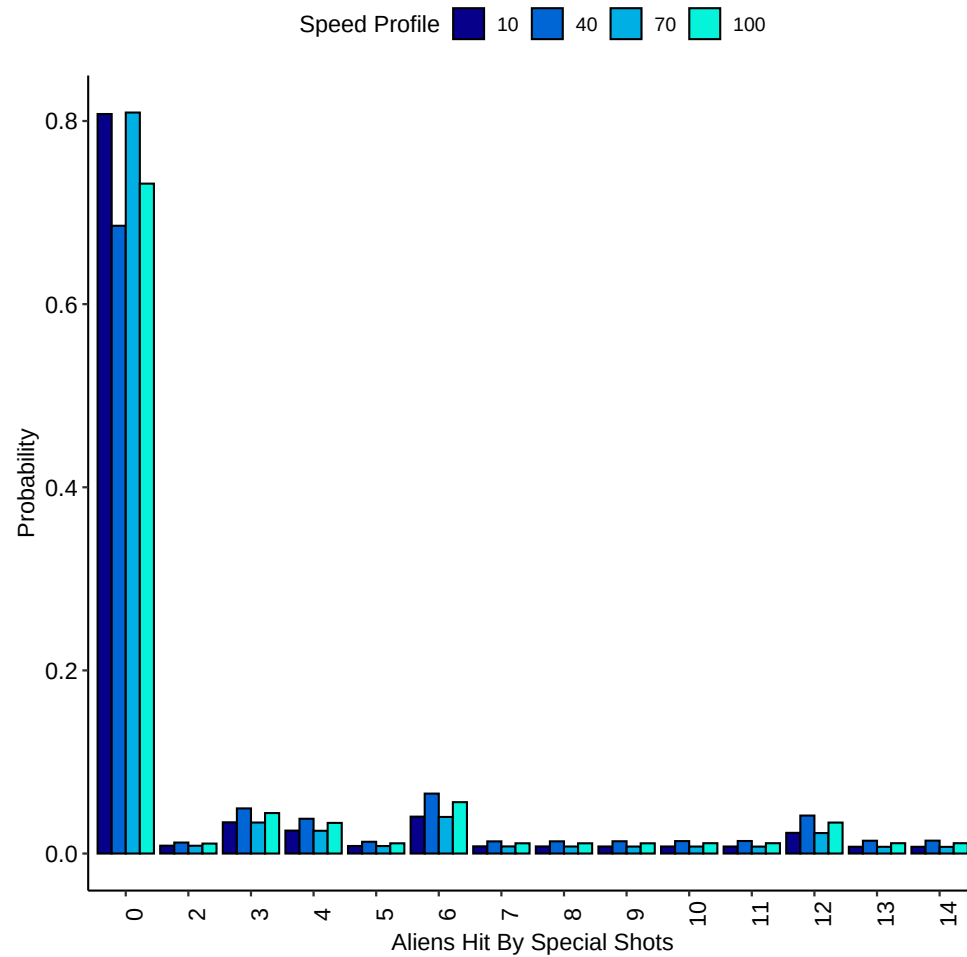


Figure E.26: Probabilities of Aliens Hit by Laser and Big Shots average scores for each speed profile

E.9 Game Performance - Alien Bullets Hit

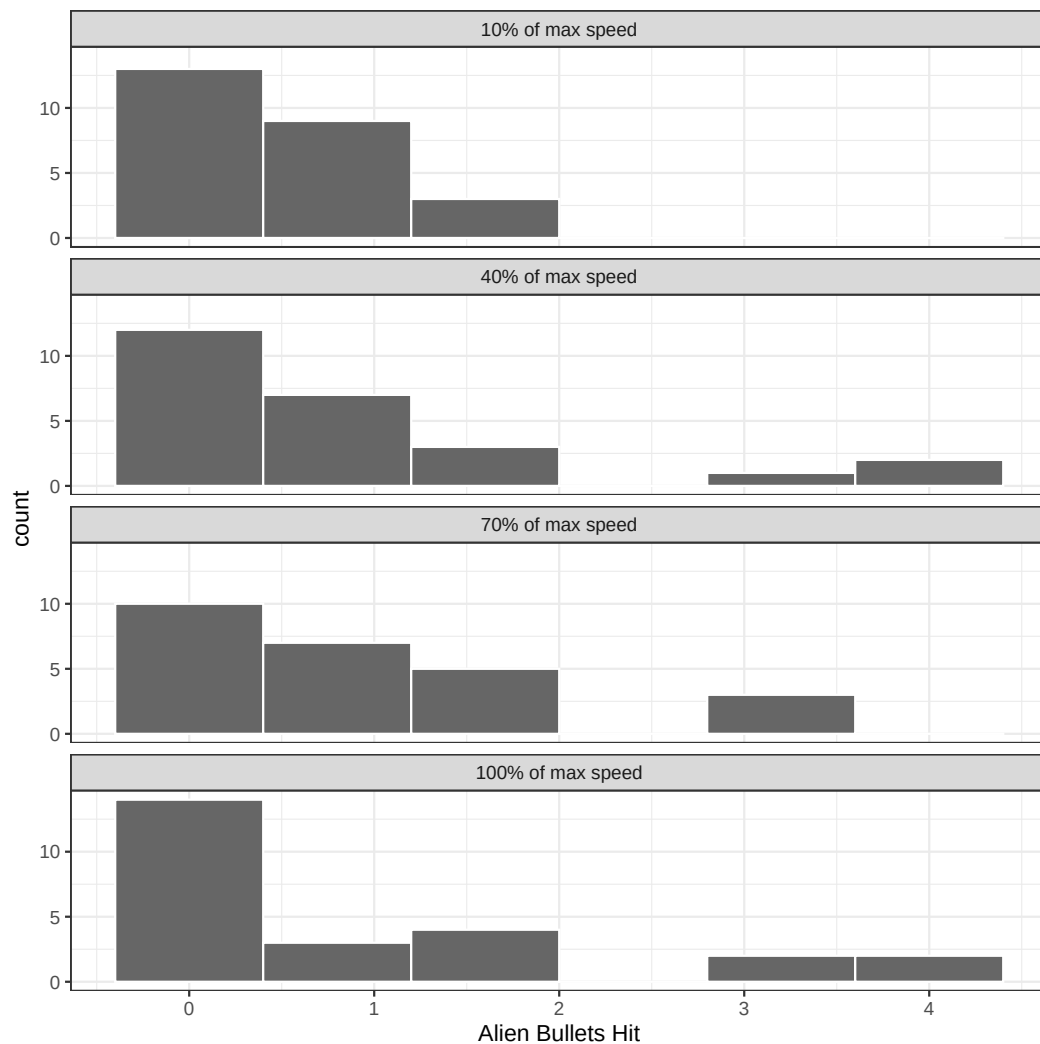


Figure E.27: Alien Bullets Hit score frequencies for each speed profile

One of the secondary tasks given to the participants was to cancel out alien bullets by shooting them. The scores for this are indicated in the *Alien Bullets Hit* category. The minimum number of alien bullets hit in this category was 0 and the maximum was 4, giving a total of 5 possible ordinal integer score outcomes. These final score value frequencies are reported in Figure E.27 for each speed profile. Means and standard deviations are summarised in Table E.25. These score averages and data distributions are visualised in Figure E.28. Shooting down these alien bullets required more accuracy, as the bullets were much smaller targets than the aliens. Visual inspection of Figure E.27 shows that most participants did not hit any alien bullets at all, most likely due to them being focused on the primary task of shooting down the aliens. The score averages for *Alien Bullets Hit* indicated a small but clear increase

Table E.25: Mean scores and standard deviation results for 10%, 40%, 70% and 100% ETHD speed profiles on Alien Bullets Hit

Speed Profile	Mean	Standard Deviation
10%	0.60	0.707
40%	0.96	1.240
70%	1.04	1.060
100%	1.00	1.350

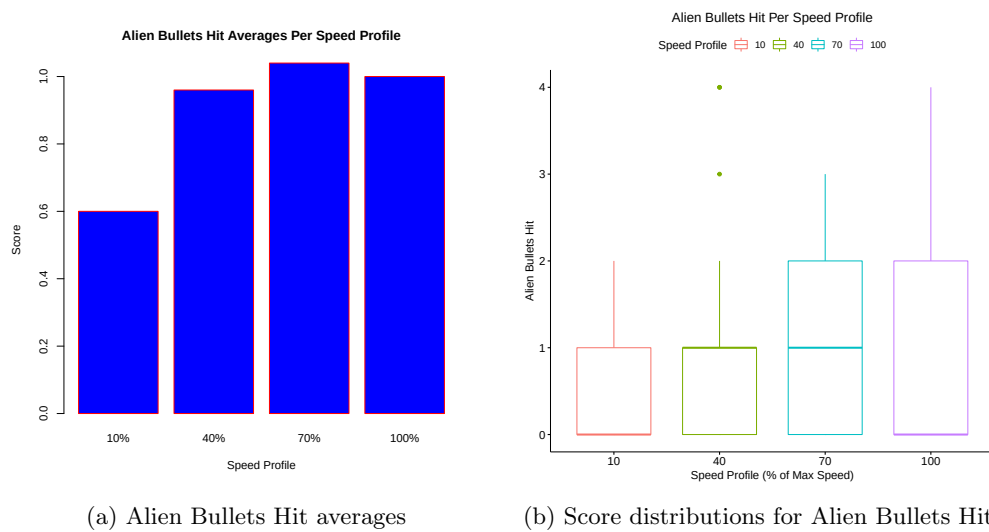


Figure E.28: Score averages and distributions for Alien Bullets Hit

in average score as the speed profile was increased, when moving from the 10% to the higher speed profiles. The average number of alien bullets hit was around one across all speed profiles. The increased responsiveness of the higher speed profiles resulted in quicker manoeuvrability to be able to shoot down these bullets, and this can be seen in Figure E.28 as the upper limits increase accordingly with the increase in ETHD speed.

The Kruskal-Wallis test was then done and resulted in $\chi^2 = 1.69$ and $p\text{-value} = 0.638$, indicating no significant differences in means. A result of $\eta^2 = -0.0136$ indicated a small effect size. Results from Dunn's test (summarised in Table E.26) also indicated no significant differences between speed profile pairs. It was noted that all differences were small and not significant. For *Alien Bullets Hit*, the results indicated an increase in average number of bullets hit as the speed profile was increased. There was not much difference in average number of bullets hit between the 40%, 70% and 100% profiles. However, moving from the 10% profile to the others resulted in large changes

Table E.26: Multiple pairwise-comparison results from Dunn’s test for 10%, 40%, 70% and 100% ETHD speed profiles on Alien Bullets Hit

Test Pair	Mean Difference	Mean Difference %	z-statistic	p -value	Significantly Different?
10-40	0.36	60.00%	0.738	0.461	No
10-70	0.44	73.33%	1.290	0.195	No
10-100	0.40	66.67%	0.615	0.539	No
40-70	0.08	8.33%	0.557	0.578	No
40-100	0.04	4.17%	-0.123	0.902	No
70-100	-0.04	-3.85%	-0.680	0.496	No

Table E.27: OLR coefficients for 40%, 70% and 100% speed profiles for Alien Bullets Hit (in relation to the 10% profile)

Speed Profile	OLR Coefficient
40%	0.3666
70%	0.6471
100%	0.2974

to the average. The largest observed was a 73.33% increase in average number of bullets hit when moving from the 10% to the 70% profile.

The coefficients from ordinal logistic regression (summarised in Table E.27) indicated that the 40%, 70% and 100% speed profiles contributed to a small increase in scores for *Alien Bullets Hit*. The 70% profile in particular resulted in the largest change with the highest coefficient of 0.6471. The probabilities for each of the possible scores arising from this model is visualised in Figure E.29. The 10% profile had the highest probability for participants to shoot zero alien bullets. The higher speed profiles had higher probabilities to get non-zero scores, with the 70% profile having the highest probabilities.

Overall, the analysis indicated that an increase in ETHD speed resulted in a small increase in scores for *Alien Bullets Hit*. The largest increase was observed for the 70% profile.

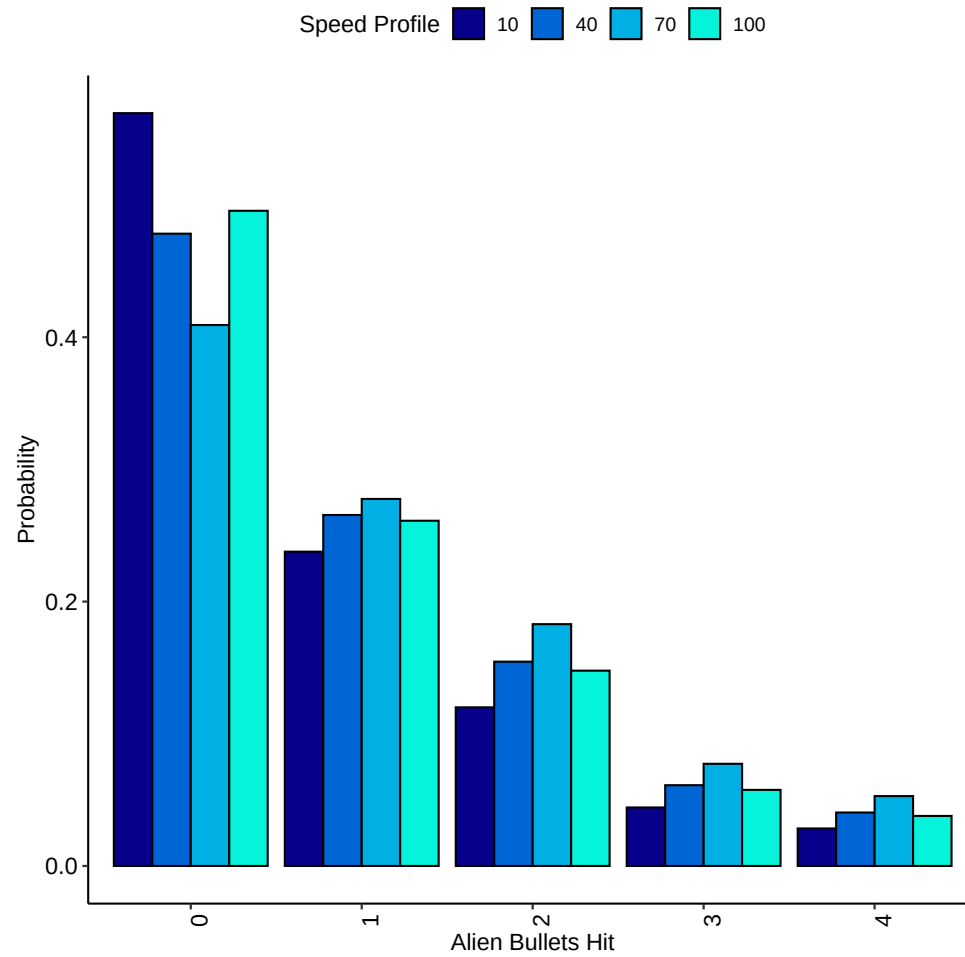


Figure E.29: Probabilities of Alien Bullets Hit average scores for each speed profile

E.10 Game Performance - Spaceship Damage

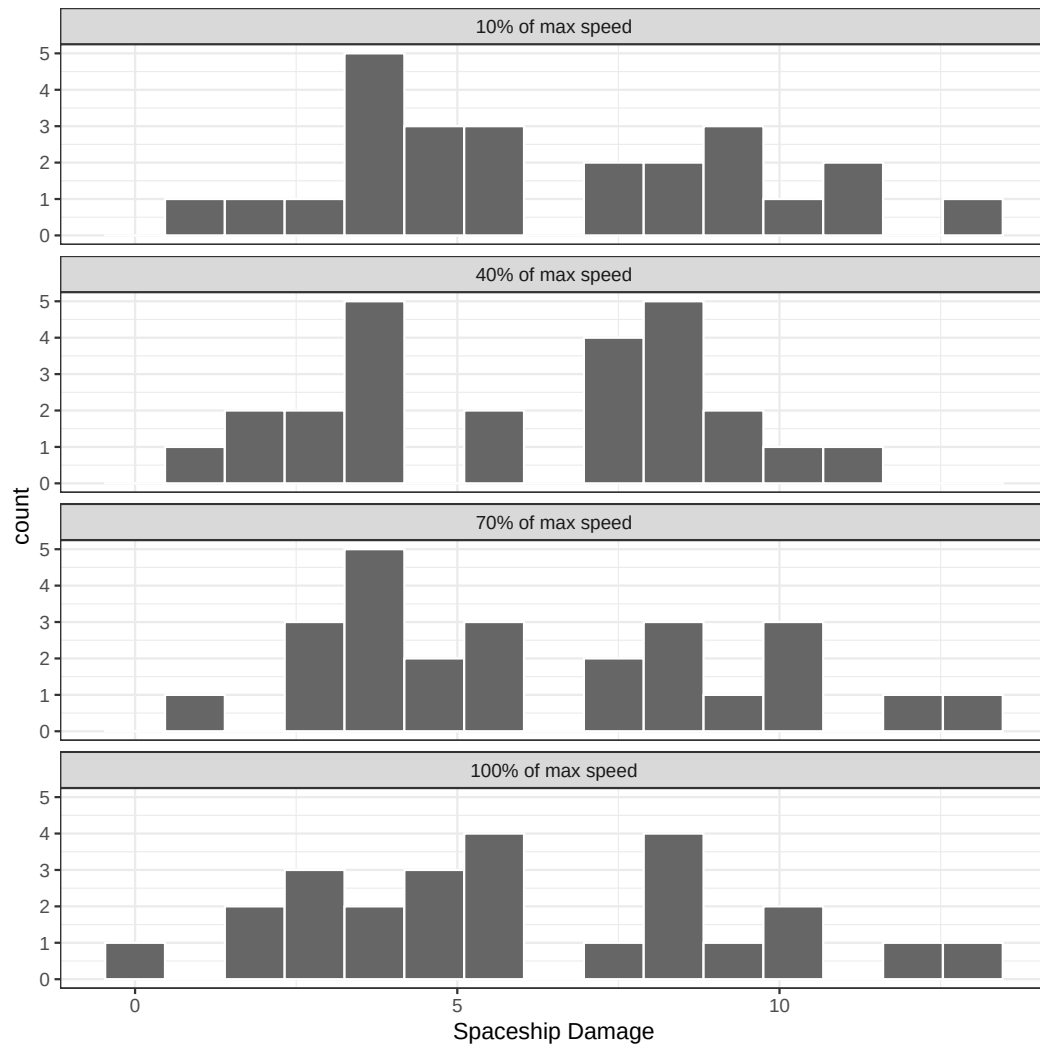


Figure E.30: Spaceship Damage score frequencies for each speed profile

Another secondary task given to the participants was to try to avoid alien bullets that would damage the player's spaceship on contact. The total number of alien bullets that made contact with the spaceship was indicated in the *Spaceship Damage* category. The minimum damage taken in this category was 0 and the maximum was 13, giving a total of 14 possible ordinal integer score outcomes. These damage value frequencies are reported in Figure E.30 for each speed profile. Means and standard deviations are summarised in Table E.28. These damage averages and data distributions are visualised in Figure E.31. These visualisations show that the damage averages dropped slightly with increasing speed profile, with the average damage taken across all profiles being around 6 alien bullets. Faster responsiveness from the ETHD at higher speed profiles would affect the manoeuvrability of the

Table E.28: Mean scores and standard deviation results for 10%, 40%, 70% and 100% ETHD speed profiles on Spaceship Damage

Speed Profile	Mean	Standard Deviation
10%	6.44	3.03
40%	6.00	2.72
70%	6.40	3.07
100%	6.12	3.22

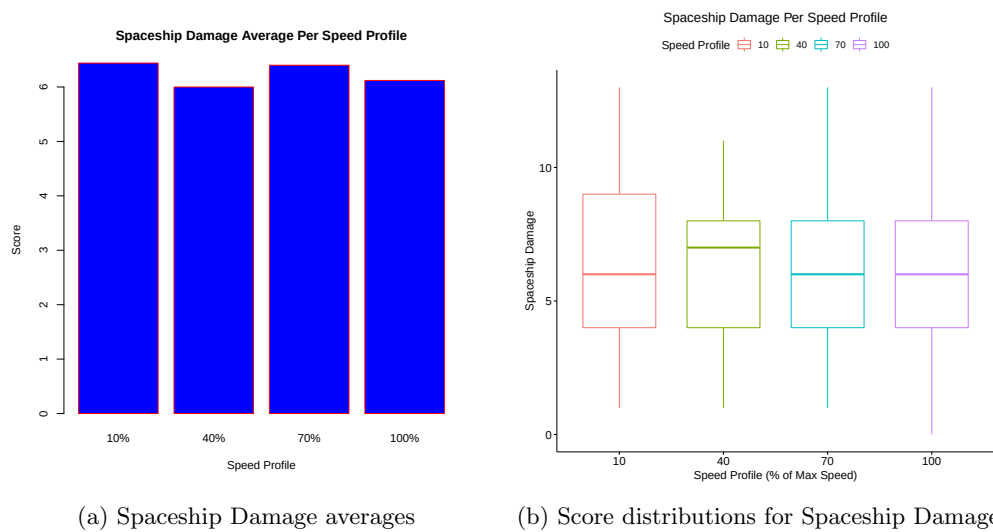


Figure E.31: Score averages and distributions for Spaceship Damage

spaceship, and how quickly a user could change direction to avoid oncoming alien bullets. Only one user managed to avoid all alien bullets, resulting in zero damage taken. This was observed on the 100% profile for this participant, showing the importance of how responsiveness affects manoeuvrability.

The Kruskal-Wallis test was then done and resulted in $\chi^2 = 0.268$ and p -value = 0.966, indicating no significant differences in means. A result of $\eta^2 = -0.0285$ indicated a small effect size. Results from Dunn's test (summarised in Table E.29) also indicated no significant differences between speed profile pairs. It was noted that although all differences were small and not significant, the results for *Spaceship Damage* indicated a slight decrease in damage taken as the speed profile was increased. The largest drop was observed when moving from the 10% to the 40% profile. The 70% profile damage average was very similar to the 10% profile. A larger sample size in future studies could clarify if this observation is consistent or if the 70% profile does drop as well with increased ETHD speed.

Table E.29: Multiple pairwise-comparison results from Dunn’s test for 10%, 40%, 70% and 100% ETHD speed profiles on Spaceship Damage

Test Pair	Mean Difference	Mean Difference %	z-statistic	p -value	Significantly Different?
10-40	-0.44	-6.83%	-0.429	0.668	No
10-70	-0.04	-0.62%	-0.120	0.904	No
10-100	-0.32	-4.97%	-0.402	0.688	No
40-70	0.40	6.67%	0.309	0.757	No
40-100	0.12	2.00%	0.027	0.978	No
70-100	-0.28	-4.38%	-0.282	0.778	No

Table E.30: OLR coefficients for 40%, 70% and 100% speed profiles for Spaceship Damage (in relation to the 10% profile)

Speed Profile	OLR Coefficient
40%	-0.2101
70%	-0.0584
100%	-0.2012

The coefficients from ordinal logistic regression (summarised in Table E.30) indicated that the 40%, 70% and 100% speed profiles resulted in a small reduction in *Spaceship Damage*. The 40% and 100% profiles in particular resulted in the largest drop in damage taken, with the smallest coefficients. The probabilities for each of the possible scores arising from this model is visualised in Figure E.32. The 10% and 70% profiles had the highest probabilities for participants to take more damage. The 40% and 100% profiles had higher probabilities for players to take less damage.

Overall, the analysis indicated that an increase in ETHD speed resulted in a small contribution to give players better manoeuvrability and take less *Spaceship Damage*.

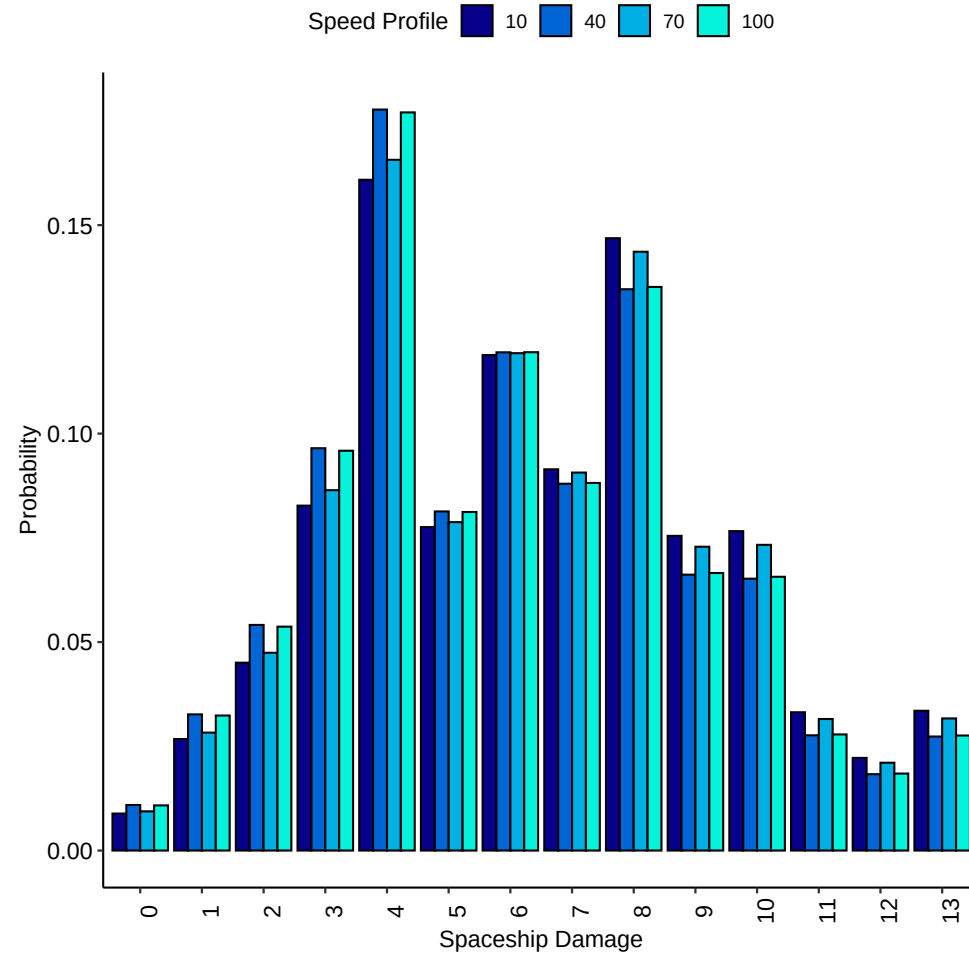


Figure E.32: Probabilities of Spaceship Damage average scores for each speed profile

Appendix F

Code Samples

Data analysis for the VR Alien Shooter Game Experiment and the VR Fitts's Test Experiment was done in RStudio. The code for this analysis can be found on Github at:

Github Repository

<https://github.com/witseie-students/2022-K-Padayachee-MSc>

The following are some of the code samples used for the main analysis of the data.

```
1 pwr.t.test(d = 0.2533108, sig.level = 0.05, power = 0.8, type = c(
  "two.sample"))
```

Listing F.1: Determining Sample Size for t-test (Effect size from Teather *et al.* [29])

```
1 pwr.t.test(d = 0.8, sig.level = 0.05, power = 0.8, type = c("two.
  sample"))
```

Listing F.2: Determining Sample Size for t-test (Large effect size)

```
1 pwr.f2.test(u=1, f2=0.35, sig.level=0.05, power=0.80)
```

Listing F.3: Determining Sample Size for Simple Linear Regression

```
1 pwr.anova.test(k = 3, f=0.4, sig.level = 0.05, power = 0.8)
```

Listing F.4: Determining Sample Size for ANOVA Test

```
1 model <- lm(AverageMovementTimeMs ~ IDe, data =
  perUserPerConditionData)
```

Listing F.5: Linear regression model for $\overline{MT}$ vs IDe .

```
1 cor.test(perUserPerConditionData$IDe, perUserPerConditionData$
  AverageMovementTimeMs, method = "pearson")
```

```

2
3 cor.test(perUserPerConditionData$IDe, perUserPerConditionData$
AverageMovementTimeMs, method = "kendall")

```

Listing F.6: Pearson and Kendall correlation tests

```

1 shapiro.test(perUserPerConditionData$AverageMovementTimeMs)
2 ggqqplot(perUserPerConditionData$AverageMovementTimeMs)
3 ggdensity(perUserPerConditionData$AverageMovementTimeMs)
4
5 shapiro.test(perUserPerConditionData$IDe)
6 ggqqplot(perUserPerConditionData$IDe)
7 ggdensity(perUserPerConditionData$IDe)

```

Listing F.7: Shapiro-Wilk normality test, density and Q-Q (Quantile-Quantile) plots for $\overline{MT}$ and IDe

```

1 library(ggfortify)
2 autoplot(model)

```

Listing F.8: Plots for linearity test (Residuals vs Fitted) and homoscedasticity test (Scale-Location)

```

1 library(lmtest)
2 lmtest::bptest(model)

```

Listing F.9: Breusch-Pagan test for homoscedasticity