Exploring Mixed Interaction Mode in Virtual Reality: Controller-based and Hand Gesture Integration

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Abstract

This research addresses the challenge of designing intuitive and effective interaction modes for object manipulation tasks in virtual reality (VR). Traditional VR interactions heavily rely on controller-based mode, which may not provide the most natural or immersive experience. In contrast, hand gesture interaction mode, enabled by technologies such as Leap Motion, offer a more natural means of interaction but often lack the precision of controller-based interaction mode. This situation opens up an opportunity to design VR interactions that seamlessly blend naturalness with precision.

This research therefore explores the benefits of a mixed interaction mode that combines the controller-based interaction mode with the hand gesture interaction mode, unlocking new possibilities for innovative and intuitive Human-Computer Interaction (HCI) in VR. The study was conducted in two phases, considering both the application scenario and the target user groups. In the first phase, 40 participants evaluated the effectiveness of the mixed interaction mode in a puzzle-solving setting. Task completion times were analysed, and participant feedback was collected to assess the combination of the controller-based and hand gesture interaction modes. Based on these findings, a second phase study was conducted in a cockpit setting to further refine the initial observations and explore the applicability and performance of the combined input approach in a specific context.

A mixed-methods analysis was conducted to evaluate the controller-based, hand gesture, and mixed interaction modes for each interaction task. The findings indicate that while the mixed interaction mode enhances the user experience, it also introduces certain challenges. Insights into VR object manipulation design guidelines were generated, suggesting that the controller-based and hand gesture interaction modes each have distinct strengths and weaknesses. The optimal interaction mode depends on the task as well as the user's experience and skill level. Further research is needed to explore the limitations and potential improvements of the mixed interaction mode, particularly in more complex tasks.

This research expands the knowledge of VR object manipulation design by summarising the suitability of interaction tasks in virtual environments. It also offers design guidelines for VR designers, enabling informed decisions when designing object manipulation tasks, and has implications for future studies in the field of VR interaction modes and user experience.

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Glossary

Term	Definition
Controller-based Mode	Controller-based mode refers to the use of handheld devices designed for VR interactions. These controllers typically feature buttons, triggers, and joysticks to enable user input within the virtual environment. This approach allows users to navigate menus, manipulate objects, and trigger actions (Fahmi et al., 2020). Devices like the HTC Vive controllers and Oculus Touch controllers are examples of technologies that use this approach.
Hand Gesture Mode	Hand gesture mode refers to an interaction approach that uses hand tracking to recognise user inputs through gestures and finger movements. This method enables a natural way for users to interact with virtual environments without the need for physical controllers. Devices such as the Leap Motion controller or those equipped with hand-tracking capabilities are examples of technologies that support this mode. (Fahmi et al., 2020; Van & Mazalek, 2011).
Interaction Mode	Interaction mode in virtual reality refers to the specific method or approach employed for user input and engagement within the virtual environment, such as using controllers, hand gestures, or eye-gaze (*Interaction — Wave vr 5.5.0 Documentation*, n.d., Strasnick et al., 2018)
Interaction Tasks	Interaction tasks in virtual reality include navigation, selection, manipulation, and system control. These tasks define how users interact with virtual environments to achieve specific objectives (Bowman et al., 2006; Chen & Bowman, 2009; Scavarelli et al., 2021)
Mixed Interaction Mode	Mixed interaction mode refers to the combination of two different interaction modes to enhance interaction in virtual environments. For example, one hand may use a handheld controller while the other employs a hand-tracking device, such as the Leap Motion, to create a hybrid input method. This combination aims to leverage the strengths of both interaction modes.

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which, to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

This following peer-reviewed paper relates directly to this doctoral thesis:

- Lee, Y., Connor, A. M., & Marks, S. (2024). Mixed Interaction: Evaluating User Interactions for Object Manipulations in Virtual Space. *Journal on Multimodal User Interfaces*, 1-15.

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I deeply appreciate the support AUT provided for awarding me the scholarship, the Sentience Lab for the availability of their technology resources, and the participants who graciously gave their time and insightful comments. Without their encouragement and input, this research project would have been less rewarding and motivating.

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This research has been approved by the Auckland University of Technology Ethics Committee (AUTEC) on 13rd June 2022, AUTEC Reference number 22/149.

Personal Statement

Over 20 years, my professional development in interdisciplinary design has been strongly influenced by design thinking. As technology integration has become more prevalent, I recognised the need to expand my knowledge of computer science and digital technologies. Pursuing a degree in Creative Technologies laid the foundation for this thesis.

Following undergraduate studies, a Master's degree in virtual reality (VR) was pursued due to its immense opportunities. The Master's thesis compared a 2D radar with a VR-enabled version in air traffic control, bridging design proficiency with virtual environments (Lee et al., 2020). This experience motivated the desire to address user interaction design in virtual spaces and to leverage design knowledge to create enjoyable virtual experiences, ultimately leading to the pursuit of a doctoral degree.

My research interests in user interaction design for VR are informed by academic knowledge of qualitative and quantitative research techniques. Experience in interdisciplinary environments has fostered respect for practice-based research in design. By adopting mixed research methods, a comprehensive understanding of results has been achieved. Quantitative data confirms key issues, while qualitative data explores users' experiences in depth.

To explore the opportunity for new interaction modes in VR, I formulated three guiding questions: "What are the current tools available for this purpose?", "What is the rationale behind creating new devices if existing ones seem sufficient?", and "What potential alternatives could a designer propose?"

Curiosity led me to question why specific tools are deemed necessary for interacting in the virtual realm when simpler means often suffice in everyday life. Through a process of reflective and iterative refinement, I employed diverse methodologies to capture the complexity of design. This research evolved dynamically, allowing for rapid topic evolution and greater confidence in the conclusions drawn.

This journey has deepened my understanding of research and broadened my perspective, providing invaluable insights for improving my future design practice. It has also highlighted the opportunity that lies in exploring new interaction modes in VR, an area that I believe holds immense potential for the future.

Chapter 1: Introduction

This chapter provides a brief introduction to the research presented in this thesis, focusing on the research background, outlining the objectives, and the structure of the thesis. It concludes with a comprehensive summary and an outline of the thesis structure. Each subsequent chapter is briefly described to provide a clear roadmap of the research journey.

1.1 Background and Motivation

While virtual reality (VR) has existed for several decades, finding the most effective methods to control it remains an ongoing challenge (Novacek & Jirina, 2020). The rapid growth of VR technologies has led to a variety of interaction modes, such as controller-based, hand gesture, voice-based, and eye-gaze-based interactions (Hasan & Yu, 2017). These modes allow diverse ways to interact with virtual elements, with body movement tracking enabled primarily through controller-based and hand gesture interactions, while voice and eye-gaze-based modes enhance interactivity by providing alternative input methods (Jankowski & Hachet, 2015; Murthy & Jadon, 2009). However, the guidelines for user engagement through these interactions remain unclear (Li et al., 2018).

Extensive research has been conducted on these technologies (Fekri & Wanis, 2019; Khundam et al., 2021; Santos et al., 2017; Wagner et al., 2021), revealing room for innovation and experimentation. While controllers have become standard tools for VR interaction, their ubiquity might be limiting the exploration of creative solutions for new interaction approaches. As per the literature, controllers, despite being effective in many respects, are limited by their design (Johnson et al., 2023). Controllers can only track certain parts of the hands, such as individual fingers, and restrict the range of hand poses that users can perform while holding them (Capece et al., 2021). Interaction approaches such as hand gesture controls, motion tracking, and haptic feedback have been found to enhance player engagement and immersion in VR games (Liao, 2023), which suggests there may be an option to consider such interaction approaches in a broader set of application areas. Particularly in VR training, hand gesture controls offer a more natural approach for simulated tasks (Khundam et al., 2021). Moreover, the development of alternative input modalities and the integration of multiple sensations have been discussed to increase the level of perceived realism in VR (You et al., 2022).

With the emergence of commercial VR Head-Mounted Displays (HMDs), the fast-paced evolution leaves certain facets, such as the impact of controller-based interaction modes on virtual experiences, yet to be fully explored (Monteiro et al., 2020). Therefore, it could be argued that the current dominance of controllers in VR might be leading to stagnation in the development of innovative interaction modes. This research therefore aims to explore current VR interaction modes by assessing the effects of three interaction modes: controller-based, hand gesture, and a combination of controller-based and hand gesture mode, referred to as mixed interaction mode. The research is as a result explorative in that it does not set out to address a defined problem, and this exploration could potentially point to new opportunities for enhancing user experience in VR.

VR can potentially transform the way of training using operational experience to improve the understanding of complex tasks and procedures (Hoang et al., 2022). However, designers and developers often face challenges when creating solutions for complex and inconsistent interaction modes involving multiple input and output devices (Dai, 2012; Hilfert & König, 2016). This research is inspired by day-to-day life activities. Humans rarely perform daily tasks using the same tools with both hands, e.g., using two knives when eating. Instead, they typically use a combination of different tools, such as a knife and a fork, each serving a unique purpose and complementing the other. This observation forms the basis for exploring the proposed mixed interaction mode in VR, which at the time this research started had not been addressed in previous studies.

Whilst some studies do undertake a comparative evaluation of different interaction modes or different object manipulation tasks (Bhowmick, 2021; Kemeny et al., 2017; Kim et al., 2022), few have looked at the combination of different interaction modes across various tasks. This indicates that the field is continuously evolving, with ongoing exploration of new ways to enhance the VR experience. This research aims to explore new interaction modes, contributing to the development of effective and user-friendly VR applications and improving the overall user experience in virtual environments.

1.2 Research Question

To explore the opportunities of interacting within VR environments beyond the use of two controllers, the central research question guiding this research is:

> **RQ**: Under what circumstances does the mixed interaction mode provide advantages for object manipulations in virtual reality compared to traditional interaction modes?

This question acknowledges that the effectiveness of mixed interaction mode in VR can be influenced by users' task performance. It underscores the significance of these factors when assessing the advantages and disadvantages of mixed interaction mode. A key outcome of this research is the insight it provides to inform future work in this field. As a result, this research provides a set of guidelines and considerations for designers aiming to create virtual environments using a mixed interaction mode. The focus is particularly on understanding and accommodating users' task performance. This approach ensures that the research findings are pertinent and applicable to a broad spectrum of VR applications and user demographics.

1.3 Significance of the Research

The significance of this research lies in its potential to transform the way users interact with virtual environments. By exploring mixed interaction mode in VR, this research could pave the way for more intuitive and immersive user experiences. The combination of a controller-based and hand gesture interaction modes could redefine the potentials for 3D object manipulation tasks in VR. The insights gained from this research could guide future work in this area, contributing new knowledge to the VR community.

This research could be particularly beneficial for designers creating virtual environments, and companies developing products that require 3D object manipulation. Moreover, the findings can have practical applications in various fields, including flight simulators and other training applications, enhancing the realism and effectiveness of virtual cockpit controls.

1.4 Structure of the Thesis

This research is divided into seven chapters. The first chapter contextualises the research, discusses the research strategy, and outlines the research problem, question, and methodology. The purpose of this chapter is to provide a framework for the research, and the remaining chapters are structured as follows:

Chapter 2 provides an overview of the existing research in the fields of VR, Human-Computer Interaction (HCI), interaction tasks, and interaction modes in VR. It further examines comparative studies and introduces the concept of mixed interaction mode. By examining these areas, it aims to identify problem domains and explore methodologies and tools.

Chapter 3 outlines the research methodology and design employed for this study, which includes two separate user studies focusing on object manipulation tasks in VR. The primary research objective is to evaluate and explore mixed interaction mode in VR. This approach directly addresses a gap identified in existing research. The literature review in Chapter 2 emphasised the limited investigation of combining different interaction modes within virtual environments. Consequently, Chapter 3 describes the selection of research tools for data collection and the subsequent data analysis process.

Chapter 4 presents the first user study, which investigates object manipulation using different interaction modes in a VR environment designed as a structured task-solving scenario. The study explores the usability, efficiency, and user experience of three interaction modes: controller-based, hand gesture, and mixed interaction mode. The chapter details the task design, user study setup, participant recruitment, and data collection process. The findings provide insights into the benefits and limitations of each interaction mode, shaping the direction for the second study.

Chapter 5 introduces the second user study, which further examines interaction tasks in a more complex VR environment. This study builds upon the insights from the first study, expanding the scope to investigate how mixed interaction mode performs in a task that involves sequential operations and precise object manipulation. The chapter covers the user study design, data collection methods, and analysis of participant feedback.

Chapter 6 provides a comprehensive discussion of the results from the two studies conducted in this research. The findings from each study are placed within the context of the relevant existing literature. To facilitate a clear and coherent discussion, the results of the first study will be examined first, followed by the discussion of the second study. The discussion addresses the research question and explores the design guidelines that emerged from the studies.

Chapter 7 summarises the research’s contribution to the field of VR development. It provides comprehensive insights into the challenges of creating and deploying immersive VR experiences. The chapter discusses hardware considerations, design implications, user behaviour, and engagement. It identifies key limitations and suggests areas for future research.

Chapter 2: Literature Review

Chapter 2 is dedicated to exploring the unique characteristics and potentials of VR, as well as the various interaction tasks that have been developed within VR technology. The main aim of this chapter is to summarise the current state of research in the field of VR and to provide a comprehensive overview of the advantages and disadvantages of different interaction modes. By understanding the current research and its limitations, this chapter focuses on analysing existing interaction modes detailed in previous research. It provides a foundation from which improved interaction modes can be proposed. This literature review utilises a technological perspective from the existing interaction task studies related to different interaction modes in a virtual environment that leads to the idea of mixed interaction mode, which combines the advantages of a controller-based and hand gesture modes to create a more natural experience.

Section 2.1 offers an overview of VR, highlighting the relationship between HCI and VR. Subsequently, Section 2.2 introduces the essential components of HCI and their relevance to current VR technologies. Section 2.3 explores the interaction in VR and considers different interaction tasks and multimodal interaction in virtual environments. Section 2.4 reviews a variety of interaction modes found in VR. Section 2.5 examines the use of comparative studies in the existing literature on VR. Section 2.6 introduces the idea of mixed interaction mode and provides an illustrative example of its potential implications. Finally, Section 2.7 summarises the considerations for VR development and the potential of a new approach to address them.

2.1 An Overview of Virtual Reality (VR)

Traditionally, VR is "the sum of the hardware and software systems that seek to perfect an all-inclusive, sensory illusion of being present in another environment" (Biocca & Delaney, 1995, p.63). Today, VR is defined as a technology used to create an immersive visual experience of complex datasets (Kapoor & Sharma, 2016) and allows users to explore and interact with a 3D environment through a wide range of new displays and input devices (Anthes et al., 2016). When integrated with display technology, users can be immersed in the synthetic world (Elmqaddem, 2019) and manipulate it directly (Bohil et al., 2011; Jerald, 2016). VR is a system capable of generating a 3D environment where "the user is an active participant and interacts with the artificial world using a range of interfaces" (Nam et al., 2018). It also allows users to interact with the virtual world by providing simulated content for the senses such as vision, hearing and touch (Fekri & Wanis, 2019). According to the existing literature, the main characteristics of VR are as follows:

- **Sense of Immersion**: It is considered to have a sense or illusion of being in the virtual environment instead of the physical world (Souza et al., 2022).
- **Navigation**: Users can move around the virtual environment using different ways, such as by walking, speaking, touching (Nam et al., 2018), or using point and teleport locomotion (Bozgeyikli et al., 2016).
- **Interaction**: It is a component that allows users to express and engage themselves with the system (Fekri & Wanis, 2019). Users can modify and manipulate the virtual objects in a range of ways in real-time (Nam et al., 2018).

Users can move around in their virtual world to increase physical activity, improving physical health and providing users with physical and cognitive benefits. For instance, research suggests that VR can increase people's confidence and physical skills (Locketz et al., 2017) and reduce depression, anxiety, and stress (Zeng et al., 2018). VR can be used to help people with physical disabilities (Lange et al., 2010; Massetti et al., 2018), such as those with sight loss (Blaha & Gupta, 2014; Younis et al., 2017) or mobility difficulties (Lee et al., 2019). Moreover, VR can also simulate dangerous and risky situations (De-Juan-Ripoll et al., 2018), allowing people to practice and develop strategies to manage them.

Furthermore, users can use their bodies to navigate the virtual space and interact with virtual objects. This natural way of interacting can help people perform complex tasks more intuitively, easily and efficiently (Bowman et al., 2008). The virtual environment also allows users to interact with 3D objects in ways that are impossible in a physical environment, such as manipulating physical properties like texture, colour, size, and shape (Mei et al., 2021). It also allows for adding sound and animation to enhance the 3D experience (Ho et al., 2019). In VR, users can directly interact with the environment by pointing, gesturing, and manipulating objects. When well-implemented, this interaction approach can offer a more intuitive and immersive way to interact with virtual content (Jerald, 2016). However, the effectiveness of such interactions depends on the specific application and implementation, as imprecise controls or task difficulties may reduce the sense of immersion.

2.1.1 Applications of VR

VR offers a range of valuable opportunities for product development and simulations (Schina et al., 2016). Specific applications include medical training (Bhagat et al., 2016), military training (Oberhauser & Dreyer, 2017), flight training (Oberhauser & Dreyer, 2017), education (Nam et al., 2018; Wang et al., 2018), architecture engineering construction (Getuli et al., 2020; Pour Rahimian et al., 2014), and other training applications, such as object manipulation training (Kangas et al., 2022), industrial training (Turner et al., 2016), and engineering design reviews (Wolfartsberger, 2019; Zhang et al., 2020). The following works of literature refer to the areas addressed to illustrate the variety of application areas.

2.1.1.1 VR for Simulation and Training

VR has been extensively used for both simulation and training purposes across various fields. One of the earliest applications of VR was in flight simulators for military training (Baumann, 1993). Today, flight simulators have become mainstream in in-flight academy schools and are accessible to the public (Rey et al., 2022). Studies have explored the use of controller-based interaction mode in flight industry-related simulators. For instance, Lee et al. (2020) suggested that VR can potentially be used in the air traffic control field, with results showing improved user performance in detecting collisions faster and more accurately than a traditional radar screen. Yavrucuk et al. (2011) reported that users feel more realistic about interacting with a virtual environment by using Data Gloves, where the pilot can press a button and reach the cockpit panel with synthetic hands. Oberhauser and Dreyer (2017) focused on the human factor aspects in the interaction with the cockpit using a touch screen prototype and collected data from the user reactions and task management in a flight simulator with a high level of fidelity. The results revealed that user movements and task completion time were slower, possibly caused by the negative feedback of non-haptic buttons. Aslandere et al. (2015) aimed for realistic interaction by comparing the performance of users with different hand avatars in button-pressing tasks. They discovered that the realism of the hand avatar had an impact on task performance, with smaller hand avatars resulting in less efficient interaction.

In the medical sector, VR is also widely used in medical training, allowing trainees to develop skills in a safe learning environment, thereby reducing the risk to patients associated with traditional learning methods (Sawyer et al., 2015). Kim et al. (2021) suggested that performance, depth accuracy and efficiency are related to haptic feedback in VR surgical tasks. Similarly, Kavanagh et al. (2017) highlighted the need for realistic experiences in VR surgical simulations to enhance learning effectiveness. The use of VR medical simulation has reached a specific standard and has significantly improved performance in basic skill training (Yiannakopoulou et al., 2015). Mackenzie et al. (2022) emphasised that it is essential to have more evaluations by experienced surgeons to achieve a better variety of skills and procedures. Chheang et al. (2019) introduced a system for laparoscopic liver surgery training, allowing two surgeons to cooperate in a virtual operating room and perform the cutting tasks. In terms of different interaction modes in this application area, Khundam et al. (2021) found no difference in interaction time and usability between hand gesture and controller-based modes for VR intubation training. However, Wonsick & Padir (2020) noted that using controller-based mode facilitated faster operation in robot control. Li et al. (2017) reviewed VR surgical simulators that interact with virtual objects using input devices like joysticks, wands, and data gloves. They suggested that an ideal VR simulator for surgical skills training should incorporate a combination of physical body models and fundamental surgical tools with VR simulators to promote interaction between practical tools and provide a multimodal training plan.

In the military sector, VR development shows the potential to change the foundation of warfare in the future. VR in military training reduces exposure to hazards, helps avoid loss and damage to humans, and increases surreptitiousness and caution (Slater et al., 2020). Bhagat et al. (2016) developed a VR military training application integrating infrared laser technology. The results indicate that VR significantly improves learning motivation and impacts user performance. Pallavicini et al. (2016) suggested that using VR in military training can decrease stress levels and positively affect military personnel. While VR in military training shows promise in reducing hazards and improving performance, it is not without its drawbacks. For instance, Harris et al. (2023) found that VR training may not fully replicate the decision-making challenges of real-life scenarios, potentially leading to a false sense of preparedness. The high costs and technical complexities of implementing VR systems can be prohibitive for some military organisations.

These studies discussed above demonstrate the use of various technologies such as Data Gloves, controllers, and touch screens, each applied in different domains for specific purposes. These technologies enhance the realism and immersion of the virtual environment, improve user perception (Novacek & Jirina, 2020), and increase motion tracking accuracy (Caeiro-Rodríguez et al., 2021). Haptic feedback, in particular, plays a significant role in improving task performance, making it essential to consider when designing VR systems for simulation and training purposes, whether in flight, medical, or military contexts. The results of these studies highlight the importance of using realistic interaction modes in VR to achieve more efficient and immersive experiences.

2.1.1.2 VR for Team Collaboration and Communications

VR technology is a powerful tool to support the architectural design process. It can provide a collaborative environment for architects and clients and help them to experience 3D spatial construction in the virtual environment (Balali et al., 2020). VR offers users to experience 3D spatial construction in a virtual environment. It has been used increasingly in architectural areas such as modelling, testing and product analysis (Erkan, 2020). Furthermore, VR enhances team performance and communication among design team members (Portman et al., 2015). The study results by Koutsabasis et al. (2012) show that VR brings an engaging experience for remote participants in collaborative work between designers and clients, where they can review the design simultaneously in the virtual environment. Similarly, Zhang et al. (2020) highlighted the contributions of VR to the construction industry, particularly in areas such as client walkthroughs and addressing the increasing need for visual communication during collaborative processes. Marks et al. (2014) demonstrated the potential of fully immersive VR systems for the visualisation of scientific and engineering data, pushing the boundaries towards creating a "Holodeck" experience.

Furthermore, VR can enhance team performance and communication between the design team members. Kingsley et al. (2017) developed an interactive platform for exploring, simulating, and communicating information about molecules. This platform allows two teams to interact with molecules efficiently and engagingly, thus enhancing research and communication between collaborators. In Collaborative Virtual Environments (CVEs), Churchill et al. (2012) discussed that users can communicate freely and collaborate effectively in shared virtual environments. In this regard, the existing works of literature provide a single interaction mode where users are encouraged to participate for better team performance and more outstanding communication actively.

2.2 Human-Computer Interaction (HCI)

HCI is the study of how humans, computers, and tasks interact, with a focus on creating technologies for people (Penichet et al., 2013). A full review of the HCI literature is beyond the scope of these thesis, which instead focuses on attempting to put interactions in virtual environments into the context of HCI. The significant components of HCI are design and user experience (Elmqvist et al., 2011). HCI aims to enable users to interact with the user interface (UI) efficiently and maintain good learnability, memorability, and usability with the system (Ghasemifard et al., 2015).

For many years, the HCI community has been striving to bridge the gap between design and research and bringing the two together in their practices (Zimmerman et al., 2007). Historically, the evolution of HCI began with the development of the first switch, which allowed users to interact with computers in a limited way. This was followed by the development of keyboard and mouse devices, which allowed users to input data and control the cursor (Murthy & Jadon, 2009). As technology has advanced, the way people interact with computers has become more natural and intuitive (Jankowski & Hachet, 2015). Multiple input devices, such as touch screens and motion sensors have allowed users to interact with computers in ways that more closely mimic how they interact with the world around them (Stephanidis et al., 2020).

For example, instead of pressing a keyboard button, users can touch a screen to select an item or move an object with a hand gesture. This interaction has made it easier for users to understand the commands and actions needed to complete tasks (Jankowski & Hachet, 2015). The development of multiple input devices has also facilitated easier access to and use of software applications. For instance, users may be able to use their voice to control a music application (Ammari et al., 2019; Janhofer et al., 2019) or use a touch-sensitive device to operate a drawing application (Blagojevic et al., 2012; Bi et al., 2011). This interface allows individuals to learn how to use software applications more quickly (Kane et al., 2008). Finally, the advancements in hardware technology, such as faster and more powerful processors, have enabled users to perform more tasks at a quicker pace (Lutteroth et al., 2015). It has helped to create better user experiences, as users can complete tasks and access information more efficiently (Zheng et al., 2014). According to Benko (2019), the timeline of UI development is summarised as follows in Table 1:

Table 1 *Interaction and Interfaces*

	Graphical User Interface (GUI)	**Natural User Interface (NUI)**	**Mixed Reality Interfaces**
Year	1980s	2000s	2020s
Input	- Mouse	- Touch/Gestures - Tablets - Smartphones	- New display form factor - New input method - New Interactions

The followings describe the characteristics of different UIs from the previous generation to the present:

- **Graphic User Interface (GUI)**
  GUI is the primary UI for interacting with computing systems with the traditional interaction style using familiar elements known as WIMP: windows, icons, menus, and pointing devices (Oulasvirta et al., 2020). GUI accepts user inputs such as mouse clicks, text entry in fields and selections. These inputs allow users to access various components of an interface (Memon, 2002) and enable user-friendly interactions with a computer-based environment (Belli et al., 2017).
- **Natural User Interface (NUI)**
  The creation of NUI attempts to establish a natural and intuitive way for humans to communicate with computers without relying on a mouse and keyboard (Glonek & Pietruszka,

2012). The interface is based on various modalities such as touch, voice recognition, human gestures, and movement detection (Kaushik et al., 2014; Jain et al., 2011; Barron-Estrada et al., 2020).

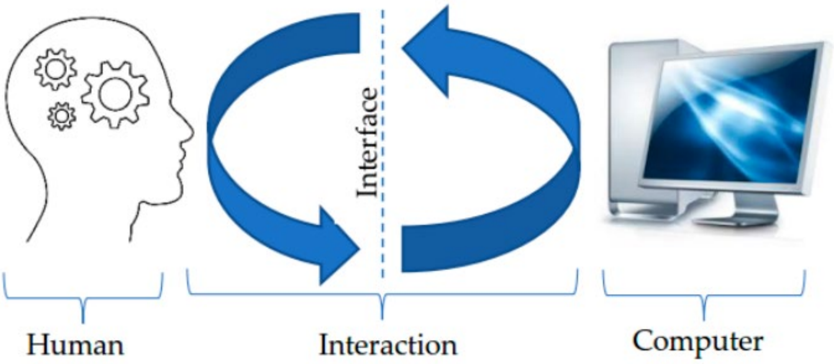
- **Mixed Reality Interface**

  The mixed reality interface aims to seamlessly link the physical and digital environments, blending objects and environments in real-time (Frank & Kapila, 2017).

The next generation of computer interfaces is expected to be adaptive and enhance universal usability (Li et al., 2022; Maiseli et., 2023; Miraz et al., 2021; Yigitbas et al., 2020). They are anticipated to blur the boundaries between the physical, virtual, and simulated worlds, ultimately creating a heightened sense of immersion (Suh & Prophet, 2018). Technologies such as augmented reality (AR), virtual reality (VR), and mixed reality (MR) offer promising opportunities in this area. AR can overlay digital information onto the physical environment, while VR and MR can completely transform the user's surroundings. These technologies create more immersive experiences, enabling users to interact with their environment naturally and intuitively (Chien et al., 2010; Wolfartsberger, 2019).

HCI is a vast field that encompasses many aspects of how humans interact with computers (Gurcan et al., 2021). While the general definition of HCI involves the planning and interaction design between humans and computers (Rodrigues et al., 2016), it also allows users to express themselves through various enhanced tools and media (Rogers, 2022). According to Norman (1986), the quality of HCI is essential and the nature of the system should be easy to learn while providing pleasure in use. The term HCI, explained in Figure 1, which includes the interfaces that enable users to interact with computer technology and engage in various activities (Katona, 2021). However, the purpose here is not to review all of HCI or go into details, but to provide a context for this research, which specifically focuses on multimodal interfaces in VR. In this context, the term HCI is used to frame the exploration of mixed interaction mode in VR and this research aims to understand how mixed interaction mode can enhance user experiences and task performance in VR, compared to traditional interaction modes.

Figure 1 *High-Level Diagram of a Typical Human–Computer Interaction (HCI)*



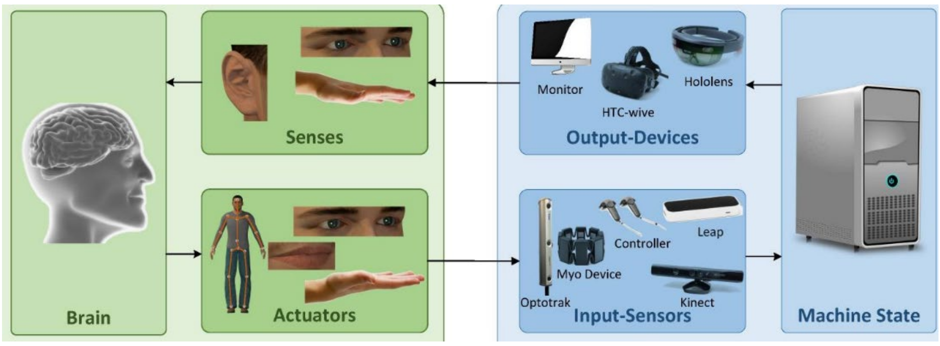
Note. This diagram refers to the interactions between computer technology and humans as user interfaces. From "A Review of Human–Computer Interaction and Virtual Reality Research Fields in Cognitive InfoCommunications," by J. Katona, 2021, *Applied Sciences*, *11*(6), p.3.

One of the key aspects of HCI in VR is the immersive experience it provides. This is achieved through the use of HMDs, 3D audio, and haptic feedback devices. These technologies create a multisensory experience that allows users to feel as though they are truly present within the virtual environment (Cardoso & Perrotta, 2019). VR is an advanced form of HCI that enables users to interact with and immerse themselves in a computer-generated environment with a sense of naturalism (Riva et al., 2016).

HCI in VR also includes natural user interfaces (NUIs). NUIs allow users to interact with the virtual environment in a way that mimics real-world interactions, including gestures, voice commands, and even eye movements. The use of NUIs in VR has been shown to enhance the user's sense of presence and immersion in the virtual environment (De Paolis & De Luca, 2020).

The development of HCI in VR represents a new way for users to input and receive information from computers, unlike traditional methods such as the mouse and keyboard, where users conduct tasks in the physical world by typing, organising files, clicking, and pointing. HCI in VR brings users closer to how they interact with their physical surroundings by simulating a virtual environment where users can move and interact with the computers. Within a virtual environment, users interact with a system composed of multiple integrated components, such as tracking sensors, input devices, and rendering engines, rather than just a single computer running standalone software. These interconnected elements work together to create a cohesive and interactive VR experience, introducing new requirements for system design and interaction approaches (Bachmann et al., 2018). Figure 2 illustrates the HCI interaction loop within a virtual environment. The human layer encompasses both the definition and execution of tasks, which are performed via the human motor or vocal system and serve as input to the computational layer. This layer receives input through specific sensors, processes it, and alters its current state. A response is then generated, which can be relayed to the user through various means such as monitors, an HMD, or audio output. The user perceives this output through their senses, completing the interaction loop (Bachmann et al., 2018).

Figure 2 *The Human-Computer-Interaction Loop*



Note. This figure shows a basic HCI interaction loop. Humans define and perform tasks using motor or vocal inputs, which are processed by the computation layer and send outputs back through senses like sight and sound. From “Review of Three-Dimensional Human-Computer Interaction with Focus on the Leap Motion Controller”, by D. Bachmann et al., 2018, *Sensors*, *18*(7), p.3.

Another important aspect of HCI in VR is the concept of user-centered design (Jerald, 2016). This involves designing VR systems with the user’s needs and capabilities in mind. User-centered design in VR focuses on ensuring that the system is intuitive to use, comfortable, and provides a satisfying user experience (LaViola et al., 2017). HCI in VR also brings new challenges in terms of usability and accessibility. Designing VR systems that are easy to use and accessible to all users, regardless of their physical abilities or technical expertise, is a major area of ongoing research in the field (Stephanidis et al., 2019).

In the realm of HCI, user experience plays a pivotal role (Clemmensen, 2024). It is shaped by the entirety of a user’s interactions with the system and its environment. Factors such as the user’s satisfaction with the system, their trust in it, and their overall experience contribute to this (Kuliga et al., 2015). Therefore, it is vital to design an intuitive, easy-to-use, and pleasant interface for the user. User experience encompasses how a person comes into contact with a product or service. In technology-related fields, user experience often involves the interaction between humans and machines and how it feels to interact with the product or service, for example, by pushing buttons

(Garrett, 2010). Designers use professional guidelines to develop an intuitive UI that allows users to understand, predict and control their interaction (Shneiderman et al., 2016). The actual usability of a VR application depends on the designers' knowledge, experience, skills, and choices (Gerhard & Norton, 2022). Usability evaluation includes the adaptability, learnability and user satisfaction of an application. Bowman (2002) explained that there are two interaction concerns with human effects in VR applications: task performance and technique performance. Task performance relates to aspects such as time to completion and accuracy, and it is measured quantitatively. Technique performance refers to the concept of usability and qualitative experience during user interaction, which includes ease of use, learning, and comfort. In the study of HCI in the context of VR, it is important to identify design solutions and address challenges like locomotion and motion sickness (Habgood et al., 2017).

Researchers have provided valuable insights into best practices in VR research. For instance, Banakou and Slater (2023) highlighted the importance of considering different methods for moving in a virtual environment when designing VR studies. Bensch et al. (2024) discussed the need for effective approaches for the evaluation and assessment of VR-based simulated training and skill acquisition tasks. Bergström et al. (2021) underscored the significance of understanding the advantages of existing methods and evaluating performance characteristics. From these insights, several key recommendations for VR studies have been derived:

1. Clearly define the evaluation goal, focusing on either speed or accuracy.
2. Use a minimum of 20 participants for analysis.
3. Control target distance by using a fixed starting position in trials.
4. Control target size by using spherical objects for selection and polyhedrons for manipulation.
5. Incorporate a variety of movement directions by placing targets across all three dimensions.
6. Control the physical setting by using a fixed user position in space.

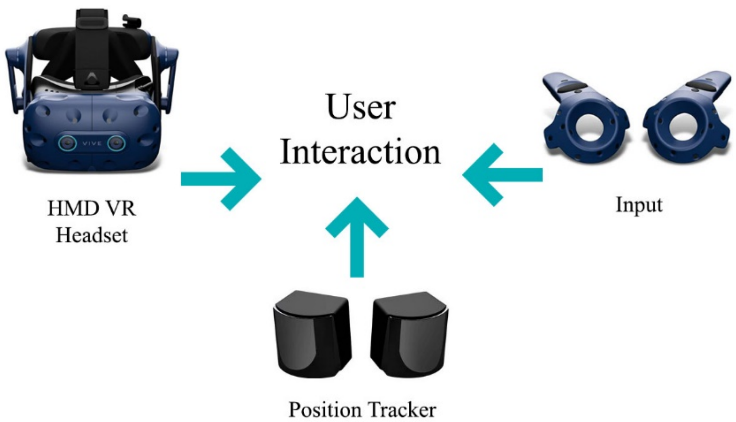
Building upon these guidelines, this research expands the knowledge in the field by exploring the mixed interaction mode. The research incorporates a combination of controller-based and hand gesture modes contributing to the development of guidelines specifically tailored to this mixed interaction mode. This approach ensures that the research findings are relevant and applicable to a wide range of VR applications and user groups.

2.3 Interaction in VR

A virtual environment offers users immersive and interactive experiences. Gerhard and Norton (2022) state that "The emergence of VR as a medium presents new, unique ways of interacting with computers. Being able to digitally generate and display content that a user's mind may interpret as a three-dimensional space introduces new ways to create and improve the way we interact." (p. 5). VR as a medium is an exciting new development in digital interaction, opening up numerous possibilities for how human interact with computers and how designers create content (Murray, 2011). The most apparent advantage of VR is that it allows users to interact with the digital world in a way that more closely resembles real-life interactions (Moustafa & Steed, 2018). VR users can move around in virtual spaces, reach out to interact with objects, and experience them in a way that feels more immersive than on traditional screens (Jones, 2017). Nevertheless, VR, HCI and human factor engineering researchers have struggled with questions about which interaction mode works best for navigation and manipulation tasks (Bowman et al., 2008).

VR interaction tasks are executed in a virtual environment that enables users to complete a virtual task through a HMD, a position tracker, and an input device (Billinghurst & Thomas, 2016). The primary components of the HTC VIVE hardware system employed in this research as shown in Figure 3, include a motion-tracked headset display, two motion-tracked hand controllers for input, and two base stations dedicated to position tracking.

Figure 3 *HTC VIVE Hardware System*



Note. From the *HTC VIVE product page*, (https://www.vive.com/us/newsroom/2020-03-02/)

2.3.1 Interaction Tasks

In order to compare the advantages and disadvantages of different interaction modes in particular tasks, this research will focus on some of the universal tasks in VR: navigation, selection and manipulation (Chen & Bowman, 2009; LaViola et al., 2017; Scavarelli et al., 2021). The following sections will further discuss their roles, challenges, and considerations in VR implementation.

2.3.1.1 Navigation

Various navigation methods are employed in VR games, each with its own advantages and limitations. Game controller-based navigation, which utilises buttons or joysticks, is commonly used for exploring expansive environments (DeYoung et al., 2018). While this method is simple and easy to use, it may not provide a natural or comfortable movement experience. Alternatively, teleportation allows users to jump from one point to another, making it useful for navigating large spaces and reducing motion sickness (Drogemuller et al., 2018). However, this method lacks real-time navigation and can diminish the sense of presence within the environment (Krekhov et al., 2018).

Embodied navigation, which involves physical movements like walking, running, jumping, and climbing, enables users to navigate the virtual environment similarly to the real-world (DeYoung et al., 2018). This method is suitable for small or confined environments but can be uncomfortable and more likely to cause motion sickness (Kemeny et al., 2017). In VR, navigation methods are primarily limited to handheld devices such as game controllers, teleportation, and embodied navigation (DeYoung et al., 2018). The main challenges in navigation design include supporting spatial awareness, providing efficient and comfortable movement, and allowing users to concentrate on other tasks (Rahimi et al., 2018; Roupé et al., 2014).

2.3.1.2 Selection

Various methods are available for object selection in VR. One approach involves tracking controllers that map the user's hand movements to a 3D cursor. With this setup, users can utilise the 3D cursor to select objects within the virtual environment (Mendes et al., 2019). Another method is eye-gaze interaction, which allows users to select objects using natural eye movements (Piumsomboon et al., 2017). Additionally, virtual hands and raycasting can be employed to select distant objects (Argelaguet & Andujar, 2013). Once an object is selected, it can be manipulated, moved, or interacted with, as outlined by Grossman and Balakrishnan (2006). Following the object selection process, subsequent actions such as manipulation and locomotion can be performed (Bhowmick, 2021).

2.3.1.3 Manipulation

Common manipulation methods in a virtual environment include moving, resizing, and rotating virtual objects (Song et al., 2012). These methods are adapted from actions typically used in 2D space, such as using a mouse cursor, pen, or touch input (Mendes et al., 2019). According to Bowman et al. (2012), manipulation tasks should include one of the three fundamental tasks: object selection, positioning, and rotation.

2.3.2 Multimodality in VR Interactions

VR is a medium that aims to simulate human sensations and interactions with the physical world (Gerhard & Norton, 2022). However, extended periods of performing various interaction tasks in a large virtual space have been found to cause fatigue (Iskander et al., 2018; Wang et al., 2019) Additionally, the use of HMDs has been associated with cybersickness, a condition characterised by symptoms such as nausea, dizziness, and visual discomfort, which can impact user experience and task performance (Rebenitsch & Owen, 2016; Saredakis et al., 2020). These challenges highlight the need to explore alternative interaction approaches, as well as environmental factors such as colour temperature, which has been shown to influence user comfort and perception (Hawes et al., 2012).

A multimodal concept involves combining multiple modalities. In the case of interfaces, a multimodal interface enhances HCI by offering more than just the keyboard and mouse as input options (Gupta et al., 2022). Multimodality in VR refers to the utilisation of multiple input modalities within the medium (Yang et al., 2019). Multimodal input in VR combines various input types, such as gestures, voice, and whole-body motion, allowing users to interact with the virtual environment using multiple modalities simultaneously (LaViola et al.,2017). This advanced form of interaction enables users to engage more naturally and efficiently by combining various sensing methods (Fekri & Wanis, 2019). By incorporating multiple modalities, users can have a seamless and intuitive experience, reducing physical movements and simulation sickness (Martin et al., 2022). Multimodal elements in VR training enhance information acquisition, understanding of concepts, and provide interactive experiences (Lu, 2013).

Incorporating broader aspects of HCI into VR is essential to improve user interaction and experience (Bowman & McMahan, 2007). Olmedo et al. (2015) emphasised that introducing multimodal interaction, including speech and gesture, significantly enriched the user experience in VR applications. They underscored the need for standardised multimodal systems to enhance usability and accessibility, allowing users to dynamically select interaction modes to meet diverse needs. Design choices play a significant role in determining the usability of VR systems (Bossavit et al., 2014).

Conducting usability testing throughout the design process is essential for evaluating ease of use, effectiveness, and user satisfaction (Chandra et al., 2019; Ogunseiju Ramaseri et al., 2022). Designers should take into account the context of use, including the user's physical environment, goals, and preferences (Keefe et al., 2005), in order to establish design principles suitable for the specific domain (Lidwell et al., 2010).

Challenges in VR multimodal interactions remain, primarily due to limited data, hardware constraints, and the need for careful design, which can impact user satisfaction and immersion (Martin et al., 2022). The synergies between different modalities in real-world scenarios need further investigation to gain a comprehensive understanding of communication (Berg & Vance, 2017). It is worth exploring whether a mixed interaction mode can address the limitations of individual modalities and if different modalities should be incorporated into a unified VR system. Further research is required to determine the optimal extent of incorporating different modalities in VR.

2.4 Interaction Modes in VR

The interaction modes in VR design are grounded in HCI principles, which guide the creation of user-centred, intuitive, and immersive experiences (Hsiao et al., 2017; Sutcliffe et al., 2019). Human-centred design, a core philosophy within HCI, emphasises creating solutions based on users' needs, context, and behaviours (Jerald, 2016; Norman, 2013). The role of HCI in VR helps to minimise cognitive load, allowing users to focus on tasks in 3D virtual environments (Araújo et al., 2016). This is achieved by the interaction modes discussed in the following sections.

2.4.1 Controller-based Interaction

A controller with buttons and switches is considered an effective way to enhance the immersive experience in VR (Choi et al., 2018). Physical controls and haptic feedback play a crucial role in improving the sense of presence by visually co-locating the controller in a virtual space with the user (Spanlang et al., 2014). These controllers enable users to interact with the virtual environment more naturally, resembling their actions in a physical space (Seibert & Shafer, 2018). The inclusion of physical controls provides feedback to the user, such as vibrations when touching objects or tactile feedback when pressing buttons, resulting in a more realistic and engaging experience (Jerald, 2016).

In the field of education, Fahmi et al. (2019) found that using a VR headset with an assigned controller can be an effective tool for studying anatomy. The controller allows users to manipulate the virtual environment easily, leading to interactive and engaging learning experiences. Similarly, in the gaming industry, Seibert and Shafer (2018) discovered that the naturalness of the controller has a significant impact on the user's game experience. Controllers that are more intuitive or mimic natural movements result in heightened levels of spatial presence. This suggests that game designers should consider the type of controller used when designing a VR game, as it can positively impact the user's experience. Furthermore, Krekhov et al. (2017) developed a self-transforming VR controller for first-person shooting games, which can alter its shape to match the currently used virtual weapon, resulting in improved aesthetics, authenticity, efficiency, realism, and immersion. In the domain of data visualisation, El Beheiry et al. (2019) focused on using a controller-based mode to visualise scientific data in the laboratory. They highlighted the importance of developing a standard interaction mode that allows users to interact appropriately with data in VR.

To enhance haptic feedback in VR controllers, Shigeyama et al. (2018) developed a dynamic weight-shifting VR controller that allows users to experience various shapes in virtual environments using a single device. Benki et al. (2016) explored handheld mechanical controllers that provide haptic feedback by simulating 3D surfaces, textures, and forces corresponding to virtual objects. These studies demonstrate the significant impact of haptic feedback on VR interaction accuracy. Researchers have suggested mechanical redesigns to improve current VR controllers by addressing issues like fatigue, discomfort, and bulkiness. These improvements aim to enhance user comfort, device effectiveness, and prevent strain on hands and wrists during prolonged use (Rantamaa et al., 2022). Incorporating tactile feedback and considering ergonomic factors in VR controller design enhances user comfort, interaction accuracy, and overall experience in virtual environments.

2.4.2 Hand Gesture Interaction

Hand gesture interaction in VR is closely related to the field of HCI (Yang et al., 2019). The release of hand tracking sensors, such as the Leap Motion controller, enables users to interact with digital content using only their hands and fingers, without any additional devices or accessories (Vosinakis & Koutsabasis, 2018). In the context of VR, hand gesture interaction provides a unique and natural way for users to interact with virtual environments, bridging the gap between physical and digital realms (Van & Mazalek, 2011). It offers advantages such as naturalness and immersion, enhancing user experience and facilitating object manipulation (Simeone et al., 2015).

Hand gesture interaction has been explored in various domains, demonstrating its effectiveness and potential impact. Studies have shown that hand gesture interaction in VR is intuitive, easy to learn and use, and causes minimal user fatigue (Zhang et al., 2017). It has been particularly effective in game-based learning, leading to improved learning performance and motor skills compared to traditional approaches (Hsiao & Chen, 2016). In the domain of therapy and rehabilitation, hand gesture interaction has been used in game-based therapy, demonstrating its effectiveness in enhancing the efficacy and engagement of therapy sessions (Gieser et al., 2016).

Furthermore, the study conducted by Jang et al. (2017) investigated the effects of hand gesture manipulation on anatomy learning in VR. The findings demonstrated that utilising hand gestures to manipulate virtual anatomical structures facilitated embodiment and resulted in improved learning outcomes. Participants who incorporated hand gestures were more successful in accurately reproducing the observed structures during the post-test compared to those who passively viewed the interactions. This highlights the significance of interactive and immersive experiences, particularly through hand gestures, in enhancing anatomy education.

While hand gesture interfaces offer advantages, they also present challenges. According to Wozniak et al. (2016), it is not advisable for developers to depend on hand gesture interfaces for sustained user experience. Hand gesture interfaces may require more time for input compared to traditional input methods like a mouse, but adaptations such as hand-adaptive UIs have shown to be more efficient, comfortable, and less physically demanding (Lou et al., 2021). Visual representation techniques can complement hand gesture interaction in VR games and training systems, enhancing users' proficiency and enabling them to perform tasks with increased speed, precision, and naturalness (Park et al., 2017; Xu, Yao, & Zhang, 2006).

To optimise hand gesture interaction in VR, researchers have highlighted important design features such as “grab size” and “release threshold”, which can enhance usability and speed up object manipulation tasks (Lin et al., 2017). Future research should also consider the interaction between gestures and the user's physical environment and limitations (Kharoub et al., 2019; Xu et al., 2020).

The existing literature provides valuable insights into the design and effectiveness of hand gesture interaction in VR. It offers a natural and immersive means of user interaction, improving user experience and facilitating object manipulation. However, careful consideration of design features, user needs, and physical constraints is necessary to ensure optimal usability and user satisfaction in VR environments.

2.4.3 Haptic Interaction

The use of haptic interaction in VR provides enhanced presence and realism, resulting in a more engaging user experience (Sutcliffe et al., 2019). Haptic interaction utilises sensors and actuators to detect pressure, movement, and temperature, which are then translated into haptic feedback, such as vibrations or pressure sensations (Pamungkas & Ward, 2016). Haptic interaction has found applications in various fields, including gaming (Foottit et al., 2016) and medical simulations (Coles et al., 2010). By delivering haptic feedback, the haptic interaction enables users to perceive details through vibrations of varying frequencies, bringing a sense of touch to virtual environments (Perret & Vander, 2018).

Research on haptic interaction has demonstrated their effectiveness in improving user interactions. For instance, Blake and Gurocak (2009) developed a VR glove with force feedback, which resulted in improved task completion times and accurate stiffness perception when grasping virtual objects. Users also found the glove comfortable to wear and easy to use. However, Jadhav et al. (2017) pointed out that haptic gloves have limitations in providing a complete sense of immersion despite their ability to offer force feedback.

In contrast, studies have shown that haptic gloves can significantly reduce execution time in tasks such as throwing and stacking (Kreimeier et al., 2019). Researchers have also focused on creating realistic finger feedback using haptic interaction, such as simulating realistic key click haptic feedback for VR keyboards (Benko et al., 2016; Wu et al., 2017). These advancements have been applied to VR rehabilitation systems, where haptic interaction have demonstrated successful operation and improved virtual rehabilitation experiences for upper limb motor skills (Borja et al., 2018).

While the existing studies on haptic interaction are limited, they provide sufficient evidence of their potential to shorten task completion times and enhance users' accuracy in perceiving stiffness. Researchers continue to explore ways to create more realistic finger feedback and improve the HCI experience by enhancing presence and realism in VR applications.

2.4.4 Eye-gaze Interaction

Real-time eye tracking technology allows users to explore and control UIs through eye movements. It provides valuable insights into user behaviour and preferences, enabling designers to improve the user experience (Hansberger et al., 2019). Eye-gaze interactions can be designed based on natural eye movements, enhancing the user experience while maintaining performance levels comparable to traditional interaction methods (Piumsomboon et al., 2017).

In VR interaction tasks, binocular eye-tracking devices have been found to offer more accurate and precise data compared to hand gestures, particularly benefiting selection tasks (Pfeiffer et al., 2008). However, eye-gaze interaction has some limitations, such as a relatively low sampling rate and lack of precision for advanced applications (Gibaldi et al., 2017). Studies have shown that the eye-gaze method can outperform head-gaze in terms of task completion time and reduced head movement (Blattgerste et al., 2018). The eye-gaze method also results in lower task load compared to head-gaze, providing a more efficient interaction (Blattgerste et al., 2018).

Eye-gaze technology can be used to gain insight into user behaviour and preferences, allowing designers to improve the user experience (Clay et al., 2019). Eye-tracking technology is a powerful tool for understanding user behaviour and improving user experiences. With proper implementation, this technology can provide valuable insights and a more immersive and efficient interaction with the proper implementation.

2.4.5 Speech-based Interaction

Speech-based interaction, enabled by speech recognition technology, allows users to communicate with computers effectively. It proves particularly beneficial when users are occupied with coordinating their hands, feet, and eyes (Jacob et al., 1993). Speech recognition enables users to control devices, issue commands, and search for information, offering a more natural and efficient interaction method compared to typing (Schalkwyk et al., 2010).

Speech technologies have diverse applications, including automatic speech recognition (ASR) for voice commands, voice biometrics for authentication, and voice synthesis for text-to-speech. These applications find utility across various domains, ranging from entertainment to healthcare and education (Ma et al., 2014). In the field of VR therapy, speech-based interaction has demonstrated its potential in treating language-related disorders, such as aphasia, dyslexia, and stuttering (Peeters, 2019). VR therapy provides a safe and controlled environment for patients to practice their language skills, leading to improvements in communication abilities (Bryant et al., 2020). Moreover, speech-based interaction in VR can be utilised to reduce public speaking anxiety (Peeters, 2019). By leveraging the immersive nature of VR, patients can engage in language exercises and receive real-time feedback, which enhances their language proficiency and confidence.

Furthermore, VR facilitates the study of language in a more naturalistic setting, providing researchers with valuable insights into the complexities of language use (Peeters, 2019). By creating virtual environments that simulate real-world language scenarios, researchers can gain a better understanding of language processing, communication dynamics, and language-related disorders.

2.5 Comparative Studies

Having reviewed interaction modes, this section focuses on studies that compare different interaction modes across VR tasks, such as navigation, selection, and manipulation, within immersive virtual environments.

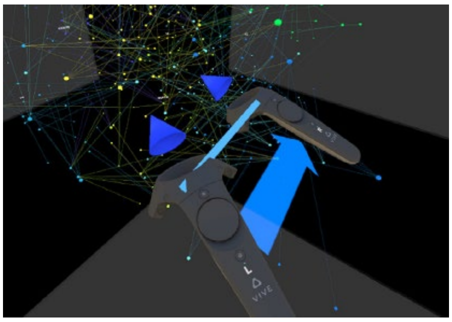
2.5.1 Navigation

Navigation is an essential component of VR experiences, and various interaction modes have been developed to support effective and efficient navigation. Riecke et al. (2010) invited participants to complete navigational search tasks with physical motion or joystick-controlled rotations and translations. The results of the study revealed that physical walking yielded far better performance than joystick navigation. Moreover, controlling translations through a joystick while rotational movements were managed by actual physical rotations led to almost similar performance to actual walking in terms of search efficiency and time.

Drogemuller et al. (2020) studied the effectiveness and performance of four different VR navigation methods – Teleportation, One-Handed Flying, Two-Handed Flying, and Worlds-In-Miniature – by having participants complete a series of tasks (Figure 4). The study results revealed that Steering Patterns (One-Handed Flying and Two-Handed Flying) were faster and more preferred by the participants for searching tasks than Teleportation. Furthermore, Worlds-In-Miniature was found to be the least physically demanding of the navigation methods and received the highest preference from participants for activities that required an overview of the environment.

Boletsis and Cedergren (2019) compared three VR locomotion methods: Walking-in-Place, controller-based mode, and teleportation. The Walking-in-Place method (Figure 5) involves the user performing virtual locomotion by standing in a fixed spot and moving as if walking. This method elicited the highest immersion but also caused considerable psychophysical discomfort. The controller-based mode was seen to be the easiest to use, given users' familiarity. At the same time, teleportation was found to be effective in terms of fast navigation, even though its visual 'jumps' disrupted the users' sense of immersion. However, teleportation can also increase disorientation and reduce a user's sense of presence within a VR environment (Habgood et al., 2018).

Figure 4 *Two-Handed Flying*



Note. Example of Two-Handed Flying, drawing an arrow between two controllers. From "Examining Virtual Reality Navigation Techniques for 3D Network Visualizations", by A. Drogemuller et al., 2020, *Journal of Computer Languages*, *56*, p.2.

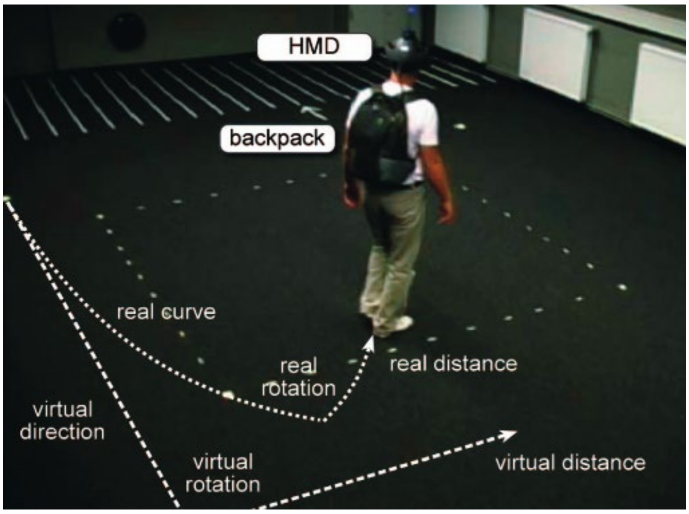
Figure 5 *Walking-in-Place*

Note. HTC Vive controllers were used to register and control VR locomotion speed and direction. From "VR Locomotion in the New Era of Virtual Reality: An Empirical Comparison of Prevalent Techniques", by C. Boletsis & J. Cedergren, 2019, *Advances in Human-Computer Interaction, 2019*, p.4.

Natural walking provides maximum immersion, reduces cognitive load, and minimises VR sickness. However, the availability of walking space affects its feasibility. When users reach the edge of the tracking space during natural walking, they often need to switch to teleportation to continue on their intended path (Liu et al., 2018). Omnidirectional treadmills have been used to enable natural walking, but they have potential limitations, such as the risk of users losing balance during turns and sidesteps (LaViola et al., 2017).

Redirected walking manipulates a user's path in the physical environment by altering the virtual environment's representations (Nilsson et al., 2018). For instance, in Figure 6, if a user walks straight in a virtual environment, redirected walking can employ visual manipulation techniques such as continuously rotating the virtual map, resulting in the user's real-world path being redirected into an arc (Steinicke et al., 2010). This method builds on real-world walking while allowing the user to explore beyond the tracked space (Cho et al., 2021). Langbehn et al. (2018) indicated that redirected walking is the most effective way to acquire spatial knowledge about a virtual environment unconsciously. It was also subjectively preferred by participants over joystick-based navigation. Furthermore, joystick-based navigation was found to cause significantly more motion sickness than redirected walking and teleportation. Therefore, redirected walking and teleportation are the most suitable locomotion methods, each with their own benefits and drawbacks.

Figure 6 *Redirected Walking Scenario*



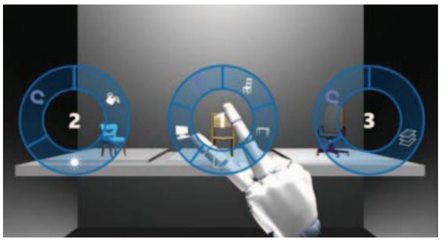
Note. A user walks a different path in the real environment than in the virtual world. From "Estimation of Detection Thresholds for Redirected Walking Techniques," by F, Steinicke et al., 2010, *IEEE Transactions on Visualization and Computer Graphics*, *16*(1), p.18.

2.5.2 Selection

Controlling a 2D UI in a virtual environment involves considering voice and gestural commands, as suggested in the research by LaViola et al. (2017). The authors argued that VR developers should explore the control mechanisms and understand the essence of the UI within their applications. By incorporating voice commands and gestural interactions, developers can enhance the user experience and provide more intuitive ways of interacting with the virtual environment.

In a related study, Davis et al. (2016) explored multi-level menus using hand gesture interaction, which can enhance the depth and complexity of menu systems in virtual environments (Figure 7). Meanwhile, comparative studies have focused on different types and designs of menus. Li et al. (2018) explored the applicability of a 3D UI canvas with pop-up and retract-back functions (Figure 8). LaViola et al. (2017) emphasised the importance of menu design, including considerations of space and size. Azai et al. (2018) proposed a Tap-Tap menu on various body parts (Figure 9).

Figure 7 *Multi-Level Menu*

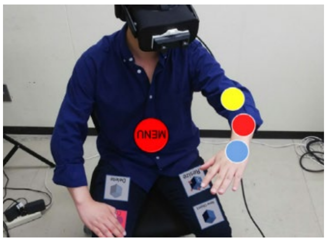


Note. GUI structure when navigating between menus. From "Depth-Based 3D Gesture Multi-Level Radial Menu for Virtual Object Manipulation," by M. Davis et al., 2016, *IEEE Virtual Reality (VR)*, p.169.

Figure 8 *3D UI Canvas*

Note. An interactive VR scene on GUI interaction. From "Applicability Analysis on Three Interaction Paradigms in Immersive VR Environment," by Z. Li et al., 2018, *2018 International Conference on Virtual Reality and Visualization (ICVRV)*, p.82.

Figure 9 *Tap-Tap Menu*



Note. Menu that is displayed on various body parts. From "Tap-Tap Menu: Body Touching for Virtual Interactive Menus," by T. Azai et al., 2018, *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology,* p.1.

Comparisons of interaction tasks with different types of menus have also been conducted. Jeong et al. (2016) compared ray casting, keypad, and hand gesture modes for point-and-click tasks in a virtual environment. Their findings indicate that ray casting offers higher speed, greater accuracy, and easier interactions than the keypad and hand gesture modes.

Ongoing studies, Monteiro et al. (2019) compared the efficiency of radial and panel menus in a virtual environment based on selection tasks. Their findings reveal that users prefer the panel menu and perform better when utilising it (Figure 10). Santos et al. (2017) investigated the effects of different menu configurations on efficiency and usability in VR, revealing that timed selection tasks are significantly faster when using the radial structure compared to the linear structure. Mundt and Mathew (2020) conducted a study comparing the usability of single-handed and two-handed radial menus, finding that the two-handed radial menu is more efficient in terms of usability, user experience, presence, error rate, and selection time.

Figure 10 *Panel Menu on the Left and Radial Menu on the Right*

Note. Panel and radial menu types with the main menu options. From “Comparison of Radial and Panel Menus in Virtual Reality,” by P. Monteiro et al., 2019, *IEEE Access*, *7*, 116373.

However, it is important to note that while many studies have focused on selection, there is a lack of evaluations on navigation and manipulation tasks in UI design. Lediaeva and LaViola (2020) examined body-referenced graphical menu placement and selection, comparing ray casting with a controller device, head, and eye-gaze (Figure 11). Their evaluation indicates that the eye-gaze mode is more prone to errors and requires more target re-entry attempts compared to controller-based and hand gesture modes.

Figure 11 *Body-Referenced Menu Placement*

Note. Spatial, arm, hand, and waist menu placements. From “Evaluation of Body-referenced Graphical Menus in Virtual Environments,” by I. Lediaeva & J. LaViola, 2020, *Graphics Interface 2020*, p.2.

The results of Kangas et al. (2022) and Nanjappan et al. (2018) suggested that different interaction modes are suitable for different types of 3D object manipulation. Hand gestures are suitable for one-hand manipulation of simple objects but are slower compared to controller-based manipulation for two-hand manipulation. Furthermore, Nanjappan et al. (2018) found that different interactions are suitable for different types of manipulation, with two-hand manipulation being best suited for controller-based manipulation.

These studies highlight the importance of user interaction research for 3D object manipulation and emphasise the need for designers to carefully consider the most suitable type of interaction for specific tasks. User studies play a crucial role in understanding which interactions are most effective for different types of manipulation.

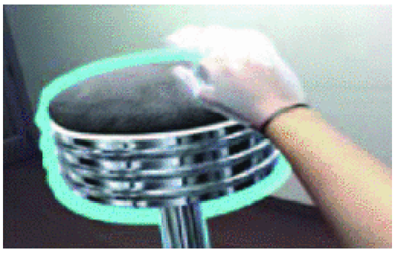
2.5.3 Manipulation

Object manipulation is a fundamental task in a virtual environment (Bossavit et al., 2014) and aims to provide a natural way to handle virtual objects in an immersive setting. A common approach in comparative studies in VR is to examine and compare controller-based and hand gesture interaction mode (Juan et al, 2023; Kharoub et al., 2019; Lin et al., 2019; Neamoniti & Kasapakis, 2022; Tanjung et al., 2020). In a controller-based interaction mode, users interact with the virtual environment using devices like controllers, joysticks, or motion-tracking devices to control their avatars (Oshita, 2006; Lugrin et al., 2018). In contrast, hand gesture interaction mode allows users to interact with the environment using body movements, such as hand gestures, to control their avatars (Murthy & Jadon, 2009; Khundam, 2015).

Previous research has compared the benefits of controller-based and hand gesture interaction tasks. For example, Kang et al. (2020) suggested that using appropriate visual cues is crucial for object manipulation tasks as it helps users understand the available interactions (Figure 12). Kharoub et al. (2019) conducted a user study to investigate the benefits of point-and-click, controller-based, and hand gesture interaction modes, focusing on manipulation and system control tasks. The study found that 80% of users expressed satisfaction with controller-based interaction, and the results indicate faster task completion times. In contrast, Lin et al. (2017) evaluated object manipulation using hand gesture interaction and found that it eliminates the need for pointing devices, resulting in cost savings, quicker operations, and reduced time and effort. Juan et al. (2023) compared two types of interaction for upper limb rehabilitation, where 78.5% of the participants preferred hand gesture interaction.
Kim et al. (2022) conducted research showing that users can easily manipulate virtual objects by testing a range of convenient object sizes for mid-air docking tasks (Figure 13). Additionally, Mendes et al. (2014) investigated user satisfaction with mid-air interactions and found that using hand gestures was regarded as more satisfying than manipulation using a handlebar. The handlebar metaphor in VR employs a virtual handlebar to manipulate a 3D object, providing visual feedback on hand orientation during interaction. The study also suggests that mid-air manipulations on virtual objects positioned above the surface closely relate to interactions in the physical world and are more appealing to users compared to objects on the surface. Song et al. (2012) emphasised that manipulation through physical

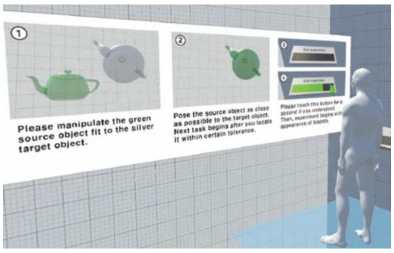
gestures supports natural and intuitive mid-air interaction by implementing a handlebar metaphor (Figure 14).

Figure 12 *Object Manipulation with Visual Cue*



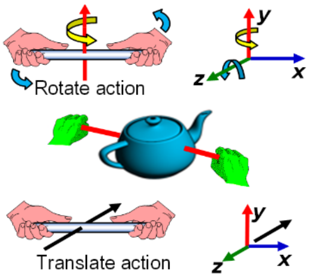
Note. Example of direct touch and grab. From “A Comparative Analysis of 3D User Interaction: How to Move Virtual Objects in Mixed Reality,” by H. Kang et al., 2020, *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, p.275.

Figure 13 *Mid-Air Object Manipulation*



Note. Rubric for a docking task. From “Virtual Object Sizes for Efficient and Convenient Mid-Air Manipulation,” by M. Kim et al., 2021, *The Visual Computer*, *38*(9–10), p.3469.

Figure 14 *Handlebar Metaphor Extended from Two Grasp Hands*



Note. A handlebar extended from clasped hands manipulates the teapot for rotation and translation. From “A Handlebar Metaphor for Virtual Object Manipulation with Mid-Air Interaction,” by P. Song et al., 2012, *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, p.1299.

Virtual object manipulation in mid-air has been identified as an efficient and convenient way to create an immersive virtual environment. Factors such as object sizes and shapes, as well as the use of hand gestures and handlebar metaphors, can impact the convenience and efficiency of these manipulations (Marti et al., 2022; Surale et al., 2019). However, the issue of fatigue associated with mid-air manipulation remains unresolved, and further research is needed to improve the overall efficiency and user comfort.

2.6 Mixed Interaction Mode

In the existing literature, various single-mode interactions in VR have been explored, such as hand gesture interaction (Khundam, 2015; Lou et al., 2021; Yang et al., 2021), haptic interaction (Boja et al., 2018; Perret & Vander, 2018; Sim et al., 2021), eye-gaze interaction (Adhanom et al., 2023; Pai et al., 2019; Plopski et al., 2022; Rahman et al., 2020), and speech-based interaction (Dhimolea et al., 2022; Ironsi, 2023). However, there is limited research on combining different interaction modes into a mixed interaction approach. This alternative approach, discussed in earlier sections, has the potential to enhance user experiences and transfer applicable design principles into virtual environments. Therefore, there is an opportunity for further exploration and research in this area.

Before considering the literature on mixed interaction mode, it is important to outline the limitations of single interaction modes in VR. Controller-based interaction provides tactile or vibrational feedback, but prolonged use can lead to fatigue. However, using a controller for extended periods can cause fatigue and discomfort, while also straining the user's hands and wrists over time (Lou et al., 2022). Hand gesture interaction offers a more natural form of interaction but can be slower for task performance (Invitto et al., 2016; Kangas et al., 2022; Masurovsky et al., 2020). Haptic gloves provide a sense of touch but lack the detail of natural touch (Yavrucuk et al., 2011). Eye-gaze interaction allows users to control UIs with their eyes but may lead to fatigue or eye strain (Chang et al., 2020; Piumsomboon et al., 2017). Lastly, speech-based interaction enables natural language commands but faces challenges with background noise and linguistic variations (Maloney et al., 2020). Understanding these limitations provides context for the potential of multiple interaction modes in VR. By combining different modes, it becomes possible to mitigate these limitations and unlock the potential.

The concept of mixed interaction in this thesis refers to a multimodal interaction method that combines controller-based and hand gesture modes simultaneously within the same virtual environment. This approach allows users to leverage their natural movements and hand gestures while also achieving precise control using a controller (Huang et al., 2021; Ionescu et al., 2011). Mixed interaction can be particularly useful in tasks that require a combination of different interaction modes, such as using a controller-based mode for precise actions and hand gestures for more expressive interactions. This could potentially provide an opportunity to enhance the user experience within VR.

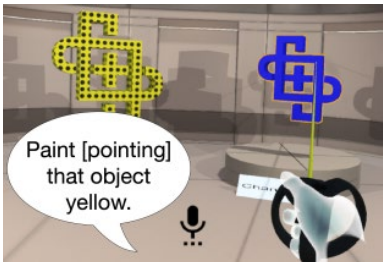
Some studies have started exploring mixed interaction in VR. For example, Sundén et al. (2017) introduced a Hybrid VR touch table that incorporates an interactive multi-touch table and combined with an HMD and an optional wireless controller (Figure 15). Their findings highlight the system's flexibility in catering to users who are interested in or prefer either of the exploratory options, as well as those with specific needs or limitations that restrict them to only one option. Wolf et al. (2019) conducted a study comparing object manipulation tasks using a combination of speech-and-gesture-based approach to a typical menu-oriented interface (Figure 16). The comparison focused on three measures: flow, usability, and presence, to evaluate the effectiveness of the speech-and-gesture-based system. The results show that the speech-and-gesture-based approach had the highest usability rating, and the fewest user errors compared to the menu-oriented interface. Additionally, the speech-and-gesture-based interface was considered the most intuitive and efficient when comparing the strengths and weaknesses of 2D UI, 3D UI, and Speech UI (Hepperle et al., 2019).

Wagner et al. (2021) attempted to evaluate interaction modes for data manipulation study using virtual hand interaction with grabbing and stretching action and virtual ray pointer with actions assigned to controller buttons and in mixed interaction mode (Figure 17). The results from 15 participants show that mixed interaction did not significantly increase workload or decrease system usability or task ease. Nevertheless, 60% of participants preferred using the mixed interaction mode for various low-level tasks over the other two modes, while 40% expressed that the mixed interaction mode could be confusing. Due to the small sample size, the results for data manipulation did not demonstrate a significant effect from using mixed interaction. The researchers suggested that designers should select interaction modes that favour specific tasks and believe that integrating different interaction modes is necessary for data manipulation in the future to overcome the limitations of specific interaction modes.

Figure 15 *Hybrid VR Touch Table*

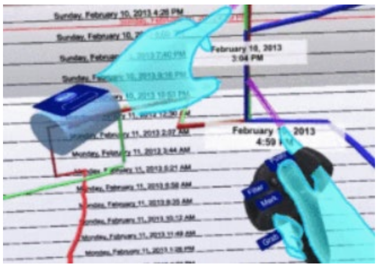
Note. Virtual exploration of the wreck site of a ship using the hybrid VR touch table. From "Hybrid Virtual Reality Touch Table—An Immersive Collaborative Platform for Public Explanatory Use of Cultural Objects and Sites," by E. Sundén, I. Lundgren, & A. Ynnerman, 2017, *Eurographics Workshop on Graphics and Cultural Heritage,* p.112.

Figure 16 *Speech-and-Gesture-Based Interface*



Note. Experiment task using multimodal techniques on an object modification process. From "Paint That Object Yellow: Multimodal Interaction to Enhance Creativity During Design Tasks in VR," by E. Wolf et al., 2019, *International Conference on Multimodal Interaction,* p.197.

Figure 17 *Mixed Interaction*



Note. Mixed interaction uses various metaphors for tasks. From "Comparing and Combining Virtual Hand and Virtual Ray Pointer Interactions for Data Manipulation in Immersive Analytics," by J. Wagner, W. Stuerzlinger, & L. Nedel, 2021, *IEEE Transactions on Visualization and Computer Graphics*, *27*(5), p.2316.

Finally, Huang et al. (2021) aimed to explore the effectiveness of combining hand gesture and controller-based modes in immersive environments. The study involved 22 participants, and the results indicated that the efficiency of task execution using hybrid inputs was comparable to using bimanual controllers. Specifically, the combination of holding a controller in the dominant hand and performing hand gestures with the non-dominant hand showed potential for efficient performance. The research provided tasks and design guidelines for the hybrid input. The guidelines are as follows:

1. **Task Suitability**: Hybrid inputs are suitable for certain types of tasks. Users show a greater willingness to use hybrid inputs when facing complicated or bimanual tasks, while they may be less interested in using them for simple tasks.
2. **Device Assignment**: Assigning the appropriate devices for each action is crucial for the effectiveness of hybrid inputs. Operations requiring stability and precise control, such as HOLD and AIM actions, should be assigned to controllers due to their better tracking capabilities.
3. **Providing Hints**: Users may make incorrect device and action pairings when using hybrid inputs. Providing hints, such as adjusting the position of game objects, can guide users to use the appropriate device for each action, enhancing performance.
4. **Consider Hand Dominance**: When the correct pairing of device and action is used, the influence of dominant and non-dominant hands becomes evident. Users often prefer using their dominant hand for actions like MOVE. Designers should consider hand dominance when designing interactions in hybrid input systems.

Despite these findings, only a few studies in the existing literature explore the potential of combined interaction, specifically for controllers and hand gestures. Huang et al. (2021) focused primarily on game-like tasks within immersive environments, which presented preliminary results that justify further research in the area.

The current research aims to contribute to this field by investigating the potential impacts of different VR interaction tasks on user performance, engagement, and experience. It extends the evaluation beyond game-like tasks to explore the effectiveness of hybrid inputs in other domains. This approach allows for a more comprehensive understanding of the usability, efficiency, and user satisfaction associated with hybrid inputs across diverse contexts. Moreover, the second phase of this research integrates simulated scenarios into the evaluation process. This integration aims to gauge the practicality and performance of hybrid input systems in settings that are relevant to their context. This second phase included simulated tasks and operations that demand precise and efficient object manipulations. By conducting evaluations in these simulated scenarios, the research builds upon the work conducted by Huang et al. (2021) and contributes to the ongoing development of knowledge regarding mixed interaction in VR.

2.7 Summary

This chapter presented the literature background of VR, the features it possesses and an overview of VR applications across various fields. It introduces the concept of HCI and its significance in the VR context. It explores the fundamental principles of VR and its applications in different domains. The discussion includes interaction in VR, focusing on interaction tasks and multimodality, which involves the use of multiple input modalities, and is also discussed as an important aspect of VR interaction.

Various interaction modes in VR, such as controller-based interaction, hand gesture interaction, haptic interaction, eye-gaze interaction, and speech-based interactions are examined in terms of its strengths and limitations. Comparative studies are discussed to compare the performance and user experience in tasks like navigation, selection, and manipulation. The findings from these studies help identify the advantages and disadvantages of each input modality.

While previous studies have focused on comparing different interaction modes, few have explored the combination of these modes. This research aims to seize the opportunity by exploring the combination of a controller-based and a hand gesture interaction, creating a mixed interaction mode. The research focuses on identifying best practices for maximising efficiency and user experience in this hybrid mode. It also considers methods of providing feedback to ensure users are aware of their actions in the VR environment. Designing an intuitive and user-friendly mixed interaction mode is another key aspect of this research, along with developing effective tutorials and feedback mechanisms to quickly familiarise users with the new mode. The existing comparison results need to be updated as new interaction modes are released in the research area and the consumer market. It is assumed that new knowledge will be discovered compared to the previous results and different interaction modes can be tested further to improve future VR user experience.

The concept of mixed interaction, which involves combining multiple input modalities, is introduced as a potential approach to enhance user interactions in VR. The chapter emphasises the need to understand the design space required for mixed interaction and how it can be mapped to available VR technologies. In conclusion, the chapter sets the foundation for the subsequent research by emphasising the importance of defining the design space for mixed interaction, particularly in the context of 3D object selection and manipulation tasks in VR.

Chapter 3: Methodology and Research Design

The research approach aims to evaluate and explore mixed interaction mode in VR, addressing an area that has received limited focus. The research consists of two studies: the puzzle study and the cockpit study. The literature review conducted in the previous chapter has highlighted the limited research on combining different interaction modes in virtual environments, which presents an opportunity for further exploration to extend the knowledge in this field.

This chapter covers the research objectives, research paradigm, and research design adopted in this research that addresses the topic of mixed interaction mode in VR. Section 3.1 outlines the specific goals and aims that the study intends to achieve as a means to inform the selection of the most appropriate research methods. Section 3.2 provides an overview of the research paradigm that guides this research. Section 3.3 describes the research design and the plan of action. It includes the specific methods chosen for data collection and evaluation, along with their underlying rationale. The research design covers each study's data collection and evaluation techniques, providing a clear roadmap for obtaining the desired outcomes.

3.1 Research Objectives

In an effort to answer the research question, this study has been designed with a clear set of aims. The following aims serve as the guiding principles for the research, providing a roadmap for the investigation and ensuring that the study remains focused on its goal of exploring the potential benefits of mixed interaction mode in VR.

- **Explore the current state**: This involves understanding the current state of interaction modes in VR, including controller-based, hand gesture, and other modes. It includes a comprehensive review of existing literature and studies on these modes.
- **Develop a mixed interaction mode**: The aim here is to design and develop a mixed interaction mode that combines elements of controller-based and hand gesture interactions. This new mode aims to leverage the strengths of both modes to enhance user experience.
- **Conduct user studies**: This involves carrying out user studies to evaluate the effectiveness of the mixed interaction mode in comparison to traditional interaction modes. These studies should involve tasks that require object manipulation in VR, such as puzzle-solving tasks and tasks in a virtual cockpit environment.

- **Analyse user performance and feedback**: This objective involves analysing user performance and gathering user feedback to assess the advantages of the mixed interaction mode. This includes metrics such as task completion time, error rate, and subjective measures of user experience.
- **Identify opportunities**: Based on the findings, the aim is to identify best practices for implementing mixed interaction mode in VR. This could include guidelines for when to use mixed interaction mode and how to design an intuitive mixed interaction interface.

By achieving these targets, the research aims to provide a comprehensive understanding of the potential advantages of using a mixed interaction mode for object manipulations in VR, compared to traditional interaction modes. This could potentially lead to new insights and opportunities for enhancing user experience in VR.

3.2 Research Paradigm

A research paradigm serves as a guiding framework that simplifies the process of making decisions about the philosophy and design of a research study (Connor, 2022). It is a pattern of choices that researchers make based on their philosophies and assumptions about the world and the nature of knowledge (Collis & Hussey, 2013, p. 43). For instance, a scientific inquiry would be guided by a paradigm that views the world as concrete, believes in the objective existence of truth, and requires experimental testing.

The two main paradigms, positivism and interpretivism, represent the extremes of a spectrum (Gasson, 2004), and their distinctions are summarised in Table 2. Positivist ontology perceives the world as external with a single, objective reality, irrespective of the researcher's viewpoint (Carson et al., 2001; Hudson & Ozanne, 1988), while interpretivist research seeks to understand the subjective experiences and meanings of human behaviour, emphasising context-specific motives and reasons over generalisation and prediction (Hudson & Ozanne, 1988; Neuman, 2000).

Table 2

A Summary of the Positive and Interpretive Approaches

Assumptions	Positivist	Interpretive
Ontological		
Nature of reality	Objective, tangible Single Fragmentable Divisible	Socially constructed Multiple Holistic Contextual
Nature of social beings	Deterministic Reactive	Voluntaristic Proactive
Axiological		
Overriding goal	"Explanation" via subsumption under general laws, prediction	"Understanding" based on Verstehen
Epistemological		
Knowledge generated	Nomothetic Time-free Context-independent	Idiographic Time-bound Context-dependent
View of causality	Real causes exist	Multiple, simultaneous shaping
Research relationship	Dualism, separation Privileged point of observation	Interactive, cooperative No privileged point of observation

However, neither of these paradigms fully aligns with the needs of this research. Therefore, the selection of an alternative paradigm becomes necessary, and there are indeed many paradigms to choose from (Gannon et al., 2022).

This research has chosen to adopt a pragmatic paradigm. Pragmatists believe that knowledge arises from a variety of specific outcomes, and it is not necessarily shaped by antecedents. They reject the idea of "predetermined frameworks" that form truth and knowledge (Easterby-Smith et al., 2021). As such, researchers who adopt a pragmatic perspective can use various approaches to understand a research problem (Maarouf, 2019). From a methodological standpoint, the pragmatic approach does not favour either inductive or deductive reasoning exclusively. Instead, it suggests that research projects can fall within the inductive-deductive research cycle at different points (Teddlie & Tashakkori, 2009).

Often referred to as the pragmatist research philosophy in the literature, a pragmatic paradigm suggests that researchers should use the methodological and philosophical approaches that yield the best outcomes for any given research problem (Tashakkori et al., 1998). Pragmatism as a research paradigm does not engage in contentious metaphysical concepts such as reality or truth. Instead, it acknowledges that there can be single or multiple realities open to inquiry (Creswell & Clark, 2017, p.45). Therefore, a pragmatic paradigm allows researchers to accept certain paradoxes and adjust, change, and combine perspectives to produce research projects that sit outside accepted conventions (Connor, 2022). This approach allows the research to focus on the research design, rather than being constrained by a specific methodology. It provides the flexibility needed to explore the research question effectively.

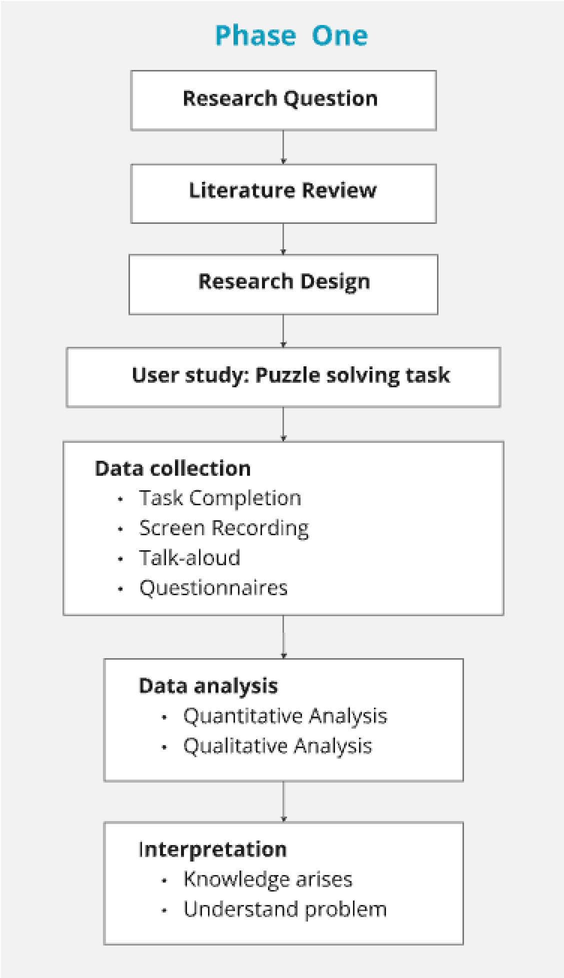
3.3 Research Design

This section outlines the research design employed in the study, detailing the methodologies and frameworks used to investigate user interactions with mixed interaction mode in VR. The research utilises a mixed-methods convergent design, integrating qualitative and quantitative approaches to provide a comprehensive understanding of user experiences and performance. The puzzle study and cockpit study are discussed, with an emphasis on data triangulation that combines surveys, talk-aloud protocols, and performance metrics to enhance the reliability of the findings.

Phase One

Once the research question is defined, the research process follows a systematic and structured framework. This framework, as depicted in Figure 18, outlines the step-by-step approach undertaken to address the research question and achieve the study's objectives. The diagram showcases the stages and key components of the research process, guiding data collection, analysis, and interpretation.

Figure 18 *Phase One Research Approach*



The puzzle study investigates participants' interactions with the controller-based, hand gesture, and mixed interaction modes in VR interaction tasks, using a mixed-methods convergent design. Qualitative methods capture user experiences and feedback, while quantitative measures task completion times for objective insights. Data triangulation was employed to integrate these data sources, ensuring that the study captures a comprehensive view of participant interactions. This sets the stage for the detailed exploration of the puzzle study in Phase 1, the specifics of which will be elaborated in the following paragraphs.

Puzzle Study

- **Objective**: Investigate how participants interact with different modes in VR object interaction tasks.
- **Design**: At first, the participants interacted with three physical cardboard puzzles, a step designed to familiarise them with the puzzles and eliminate any cognitive load concerns. Once acquainted with the puzzles, the participants transitioned to a virtual environment

where they tackled identical puzzles using three different interaction modes: controller-based, hand gestures, and a mixed approach.

- **Methods**
  - Screen Recording
  - Talk-Aloud Verbal Protocol
  - Questionnaire
- **Qualitative Approach**:
  - Allow exploration of user experiences
  - Capture participants' feedback and suggestions
- **Quantitative Approach**:
  - Numerical Data: Measures execution times
  - Statistical Analysis: Provides objective insights
- **Data Triangulation**:

  To enhance the robustness of the findings, data triangulation was employed by integrating qualitative feedback from the talk-aloud protocol with quantitative performance metrics, providing a comprehensive understanding of user interactions.

The various methods used to collect data will be introduced later in this chapter, but it is worth noting that the research is intentionally a mixed methods study, and the complexity of combining many different methods needs to be justified and the limitations acknowledged. The guiding principle used in selecting the methods was derived directly from the adoption of a pragmatic paradigm. The intention of the research was to cast a broad net in terms of data collection and accept the contradictions that arise as a result. One example of this contradiction is the combination of measuring task completion time whilst also asking participants to verbalise their thoughts. The use of a talk-aloud protocol has been shown to impact task completion time (Gill & Nonnecke, 2012). Although such contradictions are permissible within a pragmatic research framework, it is necessary to evaluate which variables are impacted and to ensure that these contradictions do not undermine the validity of the results or the research questions. These effects should be clearly acknowledged and discussed in the research.

The puzzle study examined the manipulation of relatively primitive objects, such as cubes. Simple 3D shapes are frequently used in VR studies due to their versatility in manipulation tasks (Bergström et al., 2021). The tasks involve rearranging, stacking, and fitting together objects with varying levels of complexity. This setup allows for a comprehensive examination of how the effectiveness of mixed interaction mode influences users' task performance and shapes their feedback. The puzzle study focuses on object manipulation within puzzle games, incorporating three types of puzzles: the sliding puzzle, the wood block tower, and the interlocking puzzle. These puzzles were chosen due to their varied challenges and interaction requirements, providing a diverse range of tasks for users to engage with. The sliding puzzle involves rearranging movable pieces within a grid, the wood block tower puzzle requires careful balancing and stacking of wooden blocks, and the interlocking puzzle demands analytical skills to fit multiple pieces together. This variety allows for a thorough exploration of how a mixed interaction mode can enhance users' task performance across different tasks.

During the user study, both quantitative and qualitative data were collected for subsequent data analysis. Firstly, participants were invited to solve three physical puzzles before using the VR applications: Puzzle 1, a Sliding Puzzle; Puzzle 2, a Wood Block Tower Puzzle; and Puzzle 3, an Interlocking Puzzle. Afterwards, participants were asked to solve three identical puzzles in the virtual environment. Each task was performed using different interaction modes: controller-based, hand gesture, and mixed interaction.

The following table provides an overview of the task details for each puzzle, including the required actions and objectives for participants to complete.

Table 3 *Task Details for Three VR Puzzle Types*

Puzzle Name	Task Details
Sliding Puzzle	Participants are required to slide each puzzle piece using up, down, left, and right movements until a picture of a circle is formed.
Wood Block Tower Puzzle	Participants need to stack up each wood block in a way that forms a tower structure.
Interlocking Puzzle	Participants are tasked with manipulating each wood block to interlock and form a cube shape.

The puzzle study research design incorporates mixed methods to develop a comprehensive understanding of the research objectives. The following methods were employed in this study:

Screen Recording

Screen recording was used to capture participants' interactions within the virtual environment. By documenting participants' movements and actions, researchers were able to gather empirical data on how participants coordinated their tasks (Tang et al., 2006). This method is commonly used in usability tests and allows researchers to identify potential design issues. In this study, task completion time, reset counts, and participants' behaviours were also logged for later data analysis. Data logs provide valuable insights into user interactions, helping researchers and designers understand how people engage with their products and guiding improvements in design (Gebert et al., 2020).

Talk-Aloud Verbal Protocol

During the study, participants were instructed to engage in a talk-aloud verbal protocol. They were asked to verbalise their thoughts and explain their strategies while performing the tasks in the puzzle study. The talk-aloud verbal protocol serves the purpose of capturing information about participants' cognitive processes in real-time. By speaking aloud, participants provide insights into their progress and challenges, allowing researchers to gain insights into potential issues participants may encounter and observe their ability to adapt and employ different strategies to solve the tasks (Ericsson & Simon, 1980; Van Someren et al., 1994).

Questionnaire

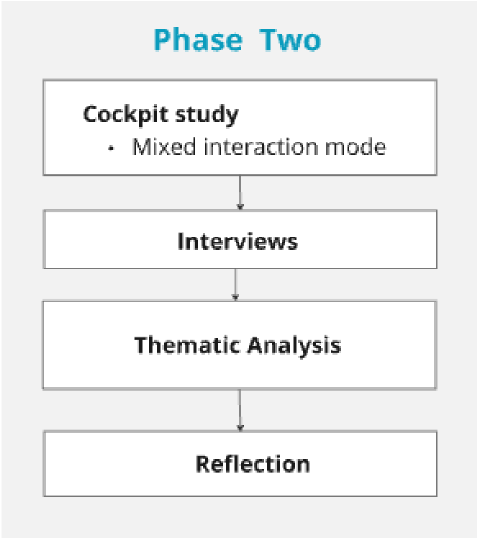
A questionnaire was administered to participants, consisting of questions related to their satisfaction with the system, ease of use, perceived mental workload, and overall opinions about the system. The questionnaire serves as a valuable tool for gathering subjective feedback on the usability and user experience of the system (Laugwitz et al., 2008). The responses obtained from the questionnaire provide valuable insights that can inform system improvements and guide future design iterations.

Phase Two

Following the puzzle study, the cockpit study was designed to further investigate the practical applicability and user experience of the mixed interaction mode in a more complex setting. The aim of this phase was to assess how the mixed interaction mode could be applied in a cockpit scenario, involving different interaction tasks compared to the puzzle study. By examining user performance and feedback, the cockpit study provided deeper insights into the strengths and limitations of the mixed interaction mode in this specific context.

A qualitative approach was used, with thematic analysis of participant interviews capturing insights into user experiences, challenges, and preferences. The analysis highlighted patterns in user feedback, contributing to the overall evaluation of the mixed interaction mode's effectiveness. Figure 19 provides a visual summary of the key insights and context-specific assessments that emerged from this phase.

Figure 19 *Phase Two Research Approach*



Building on the insights from an initial study, which focused on puzzle-solving tasks in VR, this study was conducted in a more complex environment - a virtual cockpit. This second study was not originally part of the research design but emerged as a necessary step to further explore the potential of the mixed interaction mode in a different context. This study shifted its focus to explore user experiences in the mixed interaction mode, providing a different context and set of tasks for users to engage with.

A case study is a research methodology that involves an in-depth investigation into an individual or small group of subjects within a real-world context (Yin, 2013). The cockpit study employed an explanatory sequential design, which is an ideal approach for understanding the user experience in a simulated scenario. Qualitative research methods provide an in-depth understanding of individual or small group experiences within the cockpit study, providing insight into the user experience and context. Participants were asked to sit in the middle of the room and were equipped with an HTC Vive headset and a Leap Motion controller mounted on top, along with an HTC Vive controller. In the virtual environment, participants were located inside a virtual cockpit, seated at the captain's seat on the left. They were tasked to perform various actions, such as manipulating virtual knobs, pressing buttons, pulling levers using the Leap Motion controller with their right hand, and using the HTC Vive controller to control the plane with their left hand. These actions are representative of actions in a real-world environment, though it is acknowledged that they do not encompass the full scope of actions required in piloting an aeroplane. The study consisted of six steps in the cockpit training simulator, guiding participants through specific instructions to complete the tasks.

In order to gather additional insights, interviews were conducted after each session, allowing the participants' voices to contribute in-depth details to the study (Meissner et al., 2011). Qualitative data collected from interviews with eight participants in the cockpit study enabled this research to understand the participants' experiences, motivations, and feelings regarding the research process, which provided insight into the user experience.

The cockpit study was conducted based on the outcomes of the puzzle study as a form of "purposive sampling", where it is typically designed to select a small number of cases (Teddlie & Tashakkori, 2009). In purposive sampling, the researcher has a purpose in mind and selects the participants of interest from the sample (Etikan, 2016; Miles & Huberman, 1994) that will provide the most helpful information about a situation in order to answer a research question (Teddlie & Tashakkori, 2009). In the cockpit study, the thematic analysis method is applied to the interview data, which focuses on identifying recurring words, patterns, and themes (Braun & Clarke, 2006).

This research therefore involves two studies; the detailed design of the evaluation tasks will be described in Chapters 4 and 5. The original intention was based on a single study. However, the need for a second cockpit study emerged from the results and findings from the puzzle study. As a result, this section only presents the overall intention of the research design, allowing subsequent chapters to illustrate how the second cockpit study emerged based on data collected in the puzzle study. The following sections will cover the specific details of how the methods were deployed and the data analysis approaches used.

3.3.1 Mixed Methods Research

In this research, mixed methods are used to generate a more unified conclusion by integrating qualitative and quantitative approaches. The goal is not to replace either approach but to draw from their strengths and minimise weaknesses, allowing for a comprehensive exploration of the connections between user performance and behaviours (Johnson & Onwuegbuzie, 2004). This integration of qualitative and quantitative data within a single study enables researchers to produce multi-aspect outcomes with a scientific grounding (Ivankova & Wingo, 2018). The following sections detail the application of this approach in each study:

Phase One - Puzzle Study

The convergent design, also known as the parallel or concurrent design, is a mixed methods design in which quantitative and qualitative data are collected simultaneously but analysed separately

(Creswell & Clark, 2017). This type of design allows for the collection of rich, detailed data and provides a comprehensive understanding of the research problem (Hong et al., 2017).

In the context of the puzzle study, the convergent design was particularly relevant. Quantitative data, such as task completion times and the use of hands, were collected through screen recording during the puzzle tasks. These data provided an objective measure of user performance. Concurrently, qualitative data were gathered through the talk-aloud protocol, where users verbalised their thoughts while performing the tasks. The inherent limitation of using the talk-aloud protocol whilst also measuring task completion time has already been discussed and acknowledged.

The two types of data were then analysed separately. The areas of convergence or divergence between the qualitative and quantitative results were discussed, providing a comprehensive understanding of user performance and behaviour (Xu & Storr, 2012). This approach allowed for a more nuanced understanding of what motivates and demotivates users in VR interaction. By employing the convergent design, this research was able to not only identify the factors that affect user performance and behaviour but also gain an in-depth understanding of why those factors were important. This comprehensive approach is a key strength of the convergent design and underscores its relevance to this study.

Phase Two - Cockpit Study

The explanatory sequential design is a type of mixed methods research design that is characterised by an initial phase of quantitative data collection and analysis, followed by a phase of qualitative data collection and analysis (Creswell & Clark, 2017). The purpose of this two-phase approach is to use qualitative data to help explain and contextualise the quantitative findings.

In the context of the cockpit study, this design was particularly relevant. The first phase involved the collection of quantitative data from the puzzle study. These data provided an objective measure of user performance in VR interaction tasks. However, quantitative data alone may not fully capture the complexity of user behaviours and experiences in VR. Therefore, in the second phase, qualitative data were gathered through interviews with the users. These interviews allowed for an in-depth exploration of users’ experiences, perceptions, and thoughts, providing rich, contextual insights that served to explain and provide context for the quantitative results from the puzzle study.

The explanatory sequential design thus enabled a more detailed understanding of user performance and behaviours, going beyond what could be achieved through quantitative measures alone (Gelo et al., 2008). By integrating quantitative and qualitative data, this research was able to provide a more comprehensive picture of the effectiveness and efficiency of different VR interaction modes in simulated scenarios.

Data Triangulation:

Data triangulation was used to ensure the accuracy and reliability of the results (Bekhet & Zauszniewski, 2012; Wilson, 2014). In this context, triangulation was applied to both studies using data collected from various sources. Polit and Beck (2008) identified four types of triangulation:

1. Method triangulation: This research involved using multiple methods, such as interviews and talk-aloud verbal data, to gather data. This approach offered a comprehensive understanding of user interaction processes.
2. Investigator triangulation: Multiple researchers participated in the study, providing different perspectives and interpretations of the data. Each researcher brought unique insights and observations to the study.
3. Theory triangulation: Different theories were used to analyse and interpret the data collected from the user studies.
4. Data triangulation: Data was collected from different sources. In the puzzle study, this included task completion data, talk-aloud verbal data, and questionnaires from various participants. In the cockpit study, interview data were triangulated with the puzzle study findings.

The research aimed to gather comprehensive data to explore the effectiveness of different VR interaction modes and their impact on user performance and behaviours in simulated scenarios. This involved comparing data from multiple sources, including task completion time, think-aloud verbal data, and questionnaires from the puzzle study, alongside insights from interviews in the cockpit study. By using these different data sources, the analysis aimed to identify patterns and inconsistencies, contributing to a more robust understanding of the research question. However, it is important to acknowledge the limitations of each data source, which may have influenced the consistency observed. The goal was to triangulate the data to enhance the depth of the analysis while accounting for any contradictions.

3.3.2 Puzzle Study: Data Collection and Analysis

The selection of research tools for data collection is a fundamental decision to make, and this significantly impacts the procedures of data analysis and the conclusion of the whole research (Khaldi, 2017). The two studies incorporate multi-method approaches with qualitative and quantitative data collection will be elaborated in this section.

Quantitative Data

Creswell (2014) defines quantitative research as “A means for testing objective theories by examining the relationship among variables. These variables, in turn, can be measured, typically on instruments, so that numbered data can be analysed using statistical procedures” (p.295).

Use of Hand(s) (Appendix 4) were captured during the screen recording session. Task completion time data (Appendix 1) measured the time each participant took to finish each puzzle using the three interaction modes. The reset count (Appendix 5) was recorded when the participants pressed the button to restart the puzzle. After completing the task, all participants filled in a questionnaire (Appendix 7), which included a System Usability Scale (SUS) to rate their experience and how they perceive the usability (Brooke, 2013) of each interaction mode. The questionnaire provides a single score on a scale, and it allows participants to understand (Bangor et al., 2008) the usability of the prototype easily. Questionnaires for user interaction satisfaction and usability measurements suggest how users perceive the prototype's usability when doing usability evaluations (Lewis, 2018). A NASA Task Load Index (TLX) was used to measure their mental workload (Cao et al. 2009). The TLX is often used in the HCI research community to measure factors such as work performance and productivity evaluations after the user study (Carroll & Latulipe, 2009). The TLX approach employs ordinal data, specifically a 21-point Likert scale. This scale enables respondents to express their feelings, opinions, and attitudes (Nemoto & Beglar, 2014) ranging from agreement and disagreement with a variety of statements about particular events (Taherdoost, 2019).

Qualitative Data

Creswell (2014, p.4) defines qualitative research as “A means for exploring and understanding the meaning individuals or groups ascribe to a social or human problem. The process of research involves emerging questions and procedures, data typically collected in the participant’s setting, data analysis inductively building from particulars to general themes, and the researcher making interpretations of the meaning of the data” (p.295).

In the puzzle study, the use of the talk-aloud verbal protocol was selected to conduct this evaluation. Questionnaires alone are insufficient to support an evaluation of preferences related to different interaction modes, as the actions and activities conducted in a virtual environment may be difficult to communicate verbally or may occur subconsciously, which cannot be shared as an objective evaluation. Thus, both self-recall and self-reporting do not always produce reliable data.

The talk-aloud verbal data raises participants' thoughts from their actions into awareness, providing insights into specific problem-solving and decision-making (Fonteyn et al. 1993). Participants were asked to talk-aloud during the puzzle study, and this protocol aims to collect data when participants are solving a task and are invited to explain what they think while performing the task in the user study. The input from participants will be used in this research to inform the capabilities and design of the applications. During the interaction tasks, participants were encouraged to "talk aloud," allowing them to express their preferences based on their direct experiences. It is in addition to the qualitative data collection, and the talk-aloud protocol allows them to directly shape how the outcomes of this research may be helpful to each participant and the wider VR research community.

Data Analysis

In the puzzle study, the data analysis process occurred after the data had been collected from the user study. The study involved participants completing three different tasks: the Sliding Puzzle, Wood Block Tower Puzzle, and Interlocking Puzzle. Each task was performed using different interaction modes: controller-based, hand gesture, and mixed interaction. Participants were asked to complete the tasks sequentially, from left to right in the virtual space.

Once the data was collected, the analysis process began. All the data was inspected for normality, variations, and relationships to determine the appropriate tests to be used based on the specific data types. The time taken to complete each task was one of the variables measured during the study. The Shapiro-Wilk test was employed to assess the normality of the task completion data. Levene's test was used to check for homogeneity of variances in the datasets (Gastwirth et al., 2009).

In this study, the same participants interacted with each mode, meaning the measurements are not independent but related or paired. This makes the Friedman test a suitable choice, as it is designed for repeated measures or within-subjects design where the same subjects are exposed to different conditions (Beasley & Zumbo, 2003). Furthermore, non-parametric data from multi-factor experiments, which often arise in HCI (Wobbrock et al, 2011), can therefore be effectively analysed using this method. To identify exactly which groups are different, the Conover test, a type of post hoc analysis, was used to make pairwise multiple comparisons between groups (Pereira et al., 2015).

3.3.3 Cockpit Study: Data Collection and Analysis

Qualitative Data

In the cockpit study, in-depth interviews were employed as a means to enhance the findings. As Rubin and Rubin (2011) articulated, in-depth interviewing does not strip away context or reduce people's experiences to mere numbers. Instead, it addresses a problem in its natural setting, explores related and contradictory themes and concepts, and highlights both the subtle and the explicit elements. Thus, the use of interviews proves to be a valuable tool for researchers aiming to glean insights from interactions with interviewees in their natural environments. Furthermore, Creswell (2014) suggests that an interview protocol should include the following components:

- Include date and location information on the Research Participation Invitation Form. Moreover, the interview information was recorded in a Microsoft Excel spreadsheet with basic date and location information.
- Explain the interview procedures clearly before the actual interview begins. This can be shared by sending an invitation with a brief note and providing a participant information sheet.
- Begin with ice-breaker questions, including: "Which faculty do you study?" and "Do you like playing games?" followed by four to five questions, often including the sub-questions.
- Aim for four to five questions and follow up by asking individuals to explain their ideas in detail to get more information. The interview questions were derived from the puzzle study questionnaire as follows:
  - Q1: Can you describe how you found the interaction task?
  - Q2: How demanding, both physically and mentally, did you find the task?
  - Q3: How successful do you think you were in conducting the task?
  - Q4: How did the mixed interaction mode contribute to your success?
  - Q5: What will be the difference if you were given a set of controllers or using only the Leap Motion?
  - Q6: What sort of use cases can you see as benefiting from this type of mixed interaction?
- Leave spaces between the questions to record each answer and continue with probes to allow the researcher to ask for more detail. The probes include: "Can you elaborate?", "Can you tell

me more about the VR applications that you used before, how do you feel?", "Tell me more about the different types of interaction modes used".

- A thank-you statement is a closing instruction to acknowledge the participants' time during the interview.

Data Analysis

The interview data were interpreted in relation to the context of the event and sought explanations using thematic analysis. As noted by Holstein and Gubrium (1995), "Treating interviewing as a social encounter leads us rather quickly to the possibility that the interview is not merely a neutral conduit or source of distortion but rather the productive site of reportable knowledge itself" (p. 3). Roulston (2001) also suggested that potential insights may be gained from multiple readings of particular data sets. The thematic analysis approach was applied to the interview data from the cockpit study, which involved interpretation in code selection and theme construction. The thematic analysis method was used to identify recurring words and themes (Braun & Clarke, 2012). This approach allowed the researcher to capture and arrange the data into specific patterns that provided meanings and answers to the research questions (Braun & Clarke, 2006).

3.4 Summary

The research objective is informed by existing knowledge, and the current research embraces a pragmatic paradigm. From an ontological standpoint, pragmatism acknowledges that there can be single or multiple realities open to inquiry. From an epistemological perspective, knowledge developed through a pragmatic lens is based on the outcomes of specific events or situations, rather than predetermined frameworks. This allows for a more flexible and adaptable approach to understanding the research problem.

The design of the puzzle and cockpit studies was driven by the research question, aimed at understanding the impact of different interaction modes in a virtual reality environment on user performance and experience.

In the puzzle study, tasks were selected due to the nature of puzzles, which involve clear goals and require following a step-by-step process. This means that each task in the puzzle had to be completed in a certain order, with each step building upon the one before it. These skills are integral aspects of real-world VR applications (Axelsson et al., 2001; Latham et al., 2013; Pressman et al., 2022).

The cockpit study was designed to explore a different facet of VR interaction in a complex and realistic setting. The specific tasks in this study were contingent on the precise research question. While these studies presented challenges, they offered valuable insights into VR interaction. However, results should be interpreted with caution, considering the potential influence of individual differences and task characteristics. Complementing these studies with other methods such as interviews and surveys is recommended to gain a more comprehensive understanding of user experience in VR.

The puzzle study was based on a convergent design using triangulation. Both quantitative and qualitative data were analysed statistically. The data collected from the talk-aloud protocol provided insights for the cockpit study. However, the cockpit study was based on an explanatory sequential design, which focused only on qualitative data, where the data collected from the interviews were analysed using qualitative analysis techniques that identified recurring words, patterns, and themes.

Furthermore, the cockpit study triangulated findings by comparing qualitative insights from participant interviews with the quantitative results obtained in the puzzle study, enriching the overall analysis of the mixed interaction mode.

Chapter 4: The Puzzle Study

This chapter covers the process of designing user tasks, the results and findings gleaned from the user study, and the implications of the puzzle study. Section 4.1 discusses the technical details of how the puzzle study was developed, including details on the experiments, visuals, and task designs used. The procedure for participant recruitment and user study setup is also outlined, including instructions for user tasks. Section 4.2 presents the results from the puzzle study, which included a comprehensive dataset collected from the user tasks. Section 4.3 discusses the implications and benefits of this user task design for the cockpit study. Finally, Section 4.4 describes how the results from the puzzle study inspire in forming an idea for the cockpit study later.

4.1 Design

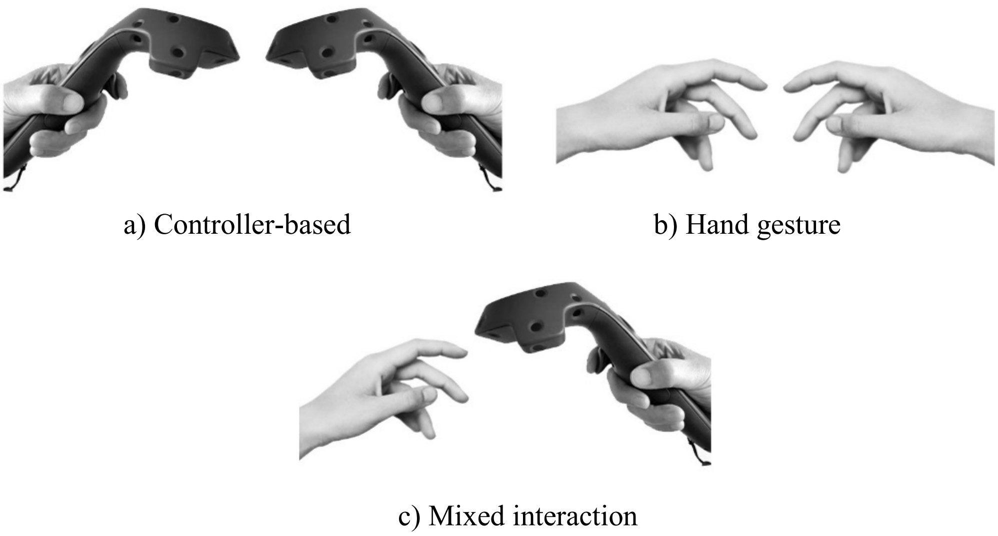
4.1.1 Software and Device

The virtual environment, including all objects and interactive elements, was designed and developed by the author using Blender and Unity. The Unity 2020.3.3 64-bit game engine (personal licence) served as the platform for developing VR applications. The research made use of three types of hardware: A HMD, the HTC Vive Pro Eye VR headset with controllers, a Leap Motion controller (Version 1), and a laptop equipped with a Core i7-9750H, 32.0 GB RAM, and a GeForce GTX 1660 Ti. The HTC Vive headset allows users to view the virtual environment. The controllers enable users to interact with objects in the virtual world, while the Leap Motion allows them to control the virtual environment with their hands.

4.1.2 Interaction Modes Setup

This research has three interaction modes: controller-based mode, hand gesture mode, and the mixed interaction mode. The interaction mechanism of each interaction mode is different. Figure 20 describes the two-handed interaction in three different modes: a) in controller-based mode, participants use the trigger button on the controller; b) in hand gesture mode, participants use a pinch gesture; c) in the mixed interaction mode, participants use the trigger button on the controller and pinch gesture.

Figure 20 *The Three Interaction Modes*



The applications were built using the Unity3D game engine with the SteamVR Plugin and Ultraleap Unity Plugin. The applications are displayed in an HTC Vive headset with controllers and tracked with Vive base stations V2.0. The concept of mixed interaction is based on having a controller and a Leap Motion within an application. The setting in the Unity3D game engine is different from a standard VR application setup, where SteamVR players and Leap Motion players are imported into one scene. As only one of each device is activated in the application, the remaining one will be turned off in the scene.

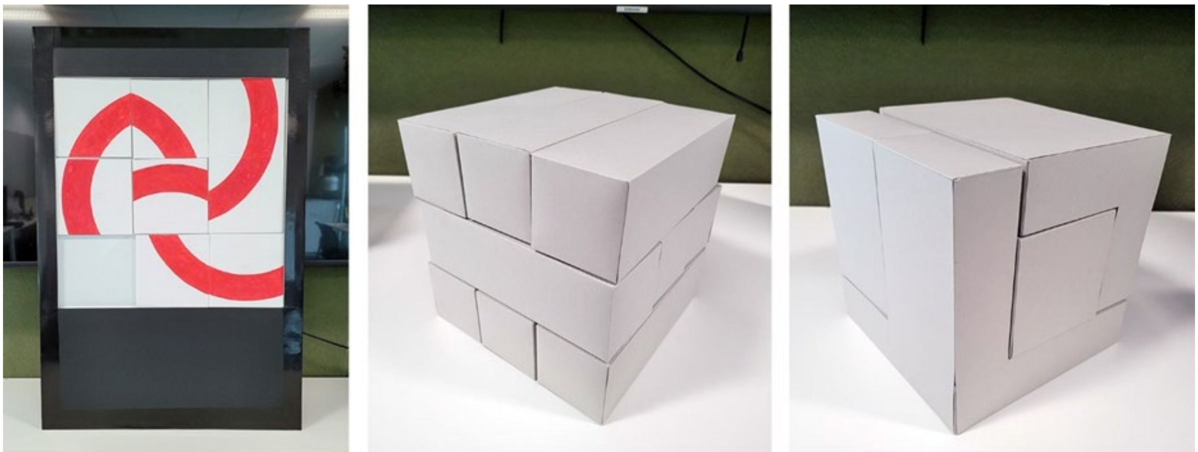
4.1.3 User Study Setup

The study incorporated physical puzzles as a reference point, building upon previous research exemplified by the Cube VR system (Axelsson et al., 2001). This earlier work revealed distinct participant engagement in virtual versus real environments during puzzle-solving tasks, making it a relevant foundation for this study. The puzzles selected - Sliding Puzzle, Wood Block Tower Puzzle, and Interlocking Puzzle - each require different types of cognitive processing and motor skills (Ayres el al., 2009; Liu et al., 2022), allowing for an assessment of the interaction modes across a range of tasks involving motor skills such as handling, orienting, and connecting puzzle pieces (Carlson, et al., 2015). Participants first engaged with the physical puzzles before transitioning to the VR environment. This approach ensured that a lack of familiarity with the puzzle’s structure did not influence task completion time, thereby isolating the variable of interaction mode.

4.1.3.1 *Physical Puzzles Setup*

Cardboard was chosen as the building material because of its lightweight, which resembles the wood block puzzles in the virtual environment. Three physical puzzles are precisely the exact sizes as in the virtual environment. In Figure 21, a) The 50 cm width x 90 cm height sliding puzzle contains eight pieces of foam boards mounted with magnets at the back, and they were placed on a metal board. This setup allows participants to slide each puzzle across until the picture of a circle is formed. b) The overall size of the wood block tower puzzle is 21 cm x 21 cm, c) The overall size of the interlocking puzzle is also 21 cm x 21 cm.

Figure 21 *Physical Puzzles*



a) Sliding puzzle b) Wood block tower puzzle c) Interlocking puzzle

The participants were asked to complete each puzzle using the hint on the left side of the table where the puzzle object was placed. The hint consisted of visual cues placed next to the puzzle object to guide the participant through the task. Each puzzle focused on different manipulation tasks. For example, Puzzle 1 involved sliding movements (Figure 22), Puzzle 2 involved grasping, holding, and moving movements (Figure 23), and Puzzle 3 explored grasping, holding, rotating, docking and motion (Figure 24). Behavioural data focusing specifically on hand(s) usage was captured during the user study, allowing comparison of how participants used single versus both hands across physical and virtual interaction modes.

Figure 22 *Participant Solving Puzzle 1*

Figure 23 *Participant Solving Puzzle 2*

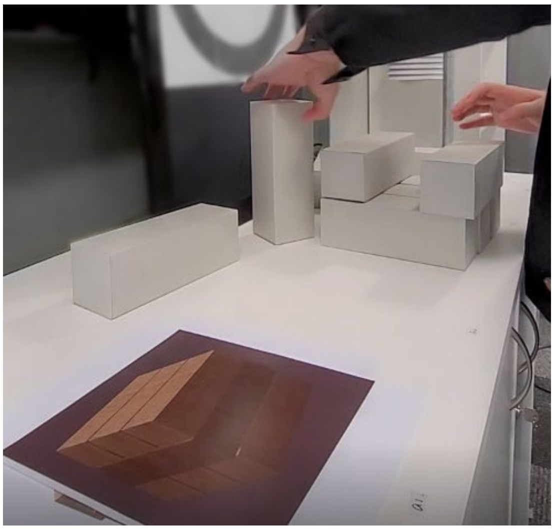
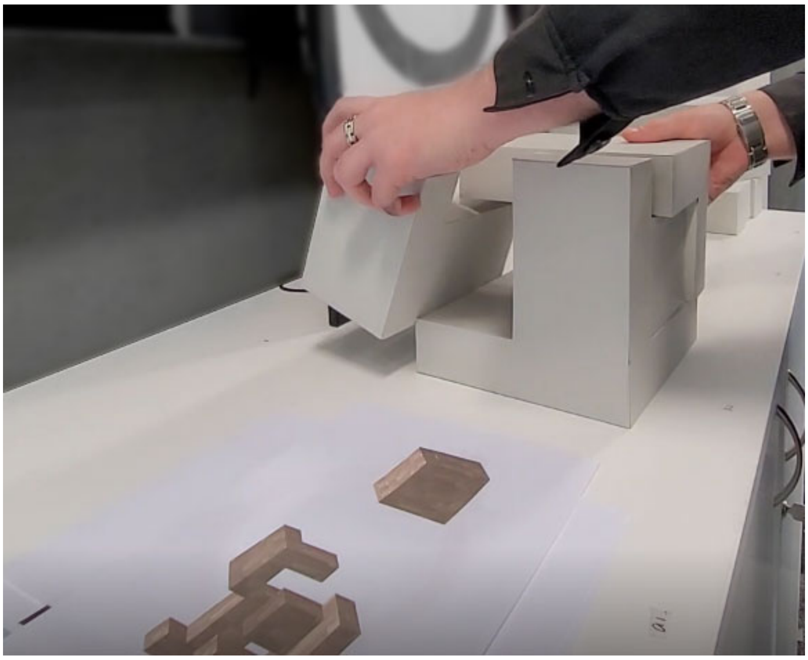


Figure 24 *Participant Solving Puzzle 3*



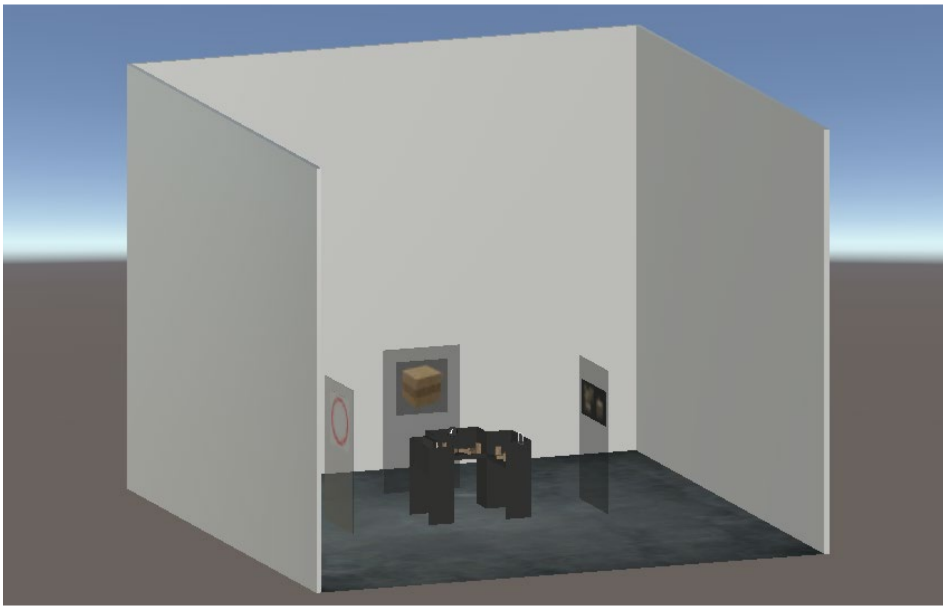
4.1.3.2 VR Setup

An HTC Vive headset with a Leap Motion mounted on top was given to each of the participants in the user study, and they were asked to stand in the middle of the room during the user study (Figure 25), which gave them space to perform manipulation tasks across three tables in the virtual environment.

Figure 25 *Participants Tested on VR Application*

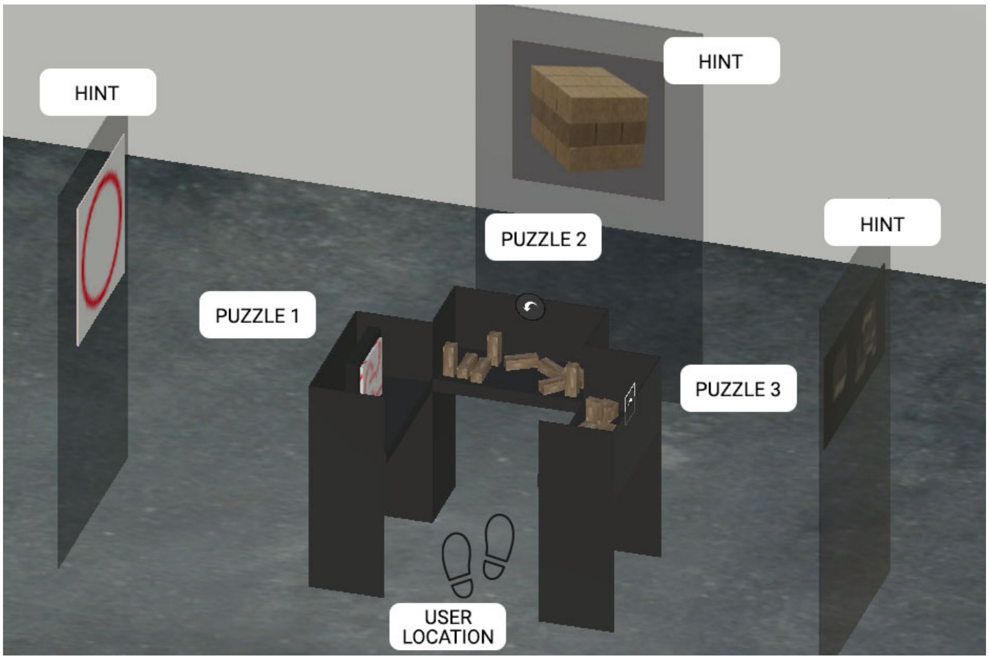
The participants were located in a virtual environment with three different puzzles on the tables in a 3m x 3m room surrounded by walls (Figure 26).

Figure 26 *Room Setup in Unity3D*



The participants were asked to complete the puzzles that focused on three basic object manipulations: grasp, hold, and move the wood blocks to match the poster with hints in front of the participants as closely as possible, as seen in Figure 27.

Figure 27 *Posters in Front of Each Puzzle*



These manipulations were performed using three different interaction modes, as depicted in Figure 28.

a) In the **controller-based mode**, both selection and manipulation of puzzle pieces were performed using the controller. This mode involves interaction with the virtual objects through a device.

b) In the **hand gesture mode**, both selection and manipulation were performed using hand gestures detected by the Leap Motion device. This mode involves interaction with the virtual objects in a manner that mimics real-world actions.

c) In the **mixed interaction mode,** users could select and manipulate objects using either the controller-based or the hand gesture modes. This mode combines both forms of interaction.

The mixed interaction mode was designed to explore whether splitting the tasks of selection and manipulation across two different interaction modes could offer a more intuitive or efficient user experience. However, it is important to note that this could potentially increase cognitive load, as the user has to manage two different interaction modalities simultaneously. The impact of this on task performance and user experience is part of what the study aimed to investigate. Further analysis of the collected data will be provided in the next section.

Figure 28 *Different Interaction Modes in VR*

a) Controller b) Leap Motion c) Mixed Interaction

4.1.4 Task Design

The VR puzzles were developed in Unity3D, with all three puzzles situated within a single scene. Participants were instructed to complete the tasks from left to right while standing in the middle of the room. The table height and dimensions of each puzzle precisely matched those of the physical puzzles. Participants first used controller-based mode to complete the three puzzles, then transitioned to the Leap Motion to tackle the same puzzles, and finally used a mix interaction mode to finish the three puzzles. This approach does lead to the possibility that users become more familiar with the interaction modes and task performance on the latter tasks is better as a result. This limitation will be discussed in more detail in Section 6.1.6 later.

4.1.4.1 Sliding Puzzle

Figures 29, 30, and 31 show the image sequences of Puzzle 1 during the user study. In these figures, participants were asked to complete the sliding puzzle using different interaction modes: a) controller-based mode, where the user’s hand holding the controller was represented by a gloved hand (Figure 29); b) hand gesture mode, where the user’s hand was represented by a low-polygon hand (Figure 30); and c) Mixed interaction mode (Figure 31).

The sliding puzzle measures 50 cm in width and 90 cm in height, and it contains 8 cubic pieces. Participants were required to slide each piece up, down, left, or right until they formed the picture of a circle.

Figure 29 *Puzzle 1 in Controller-based Mode*

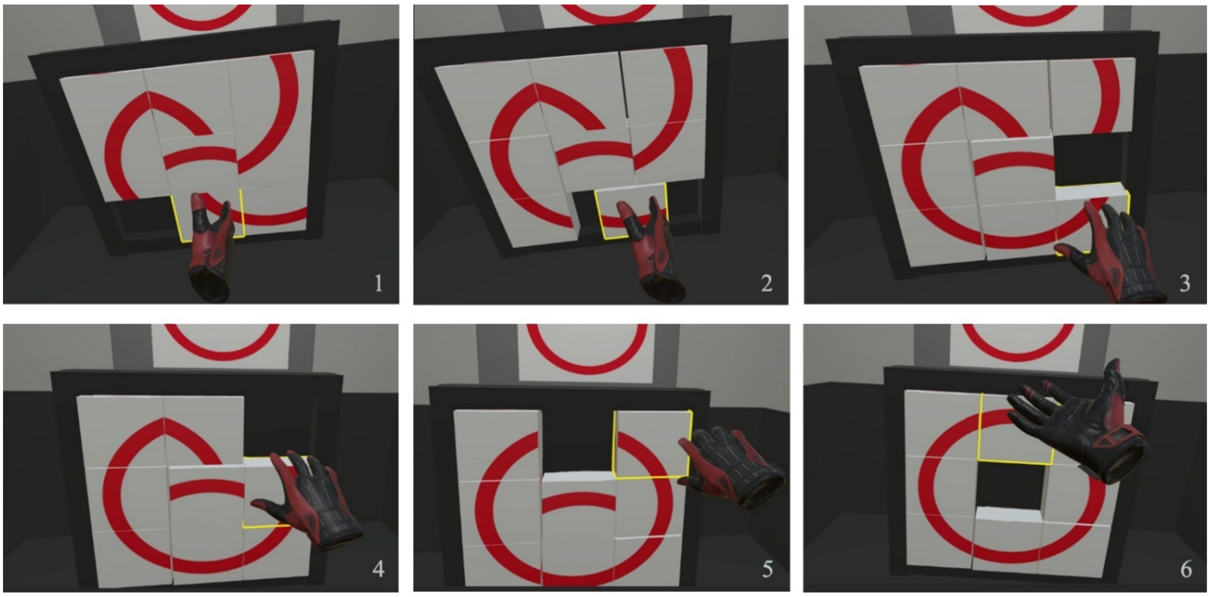


Figure 30 *Puzzle 1 in Hand Gesture Mode*

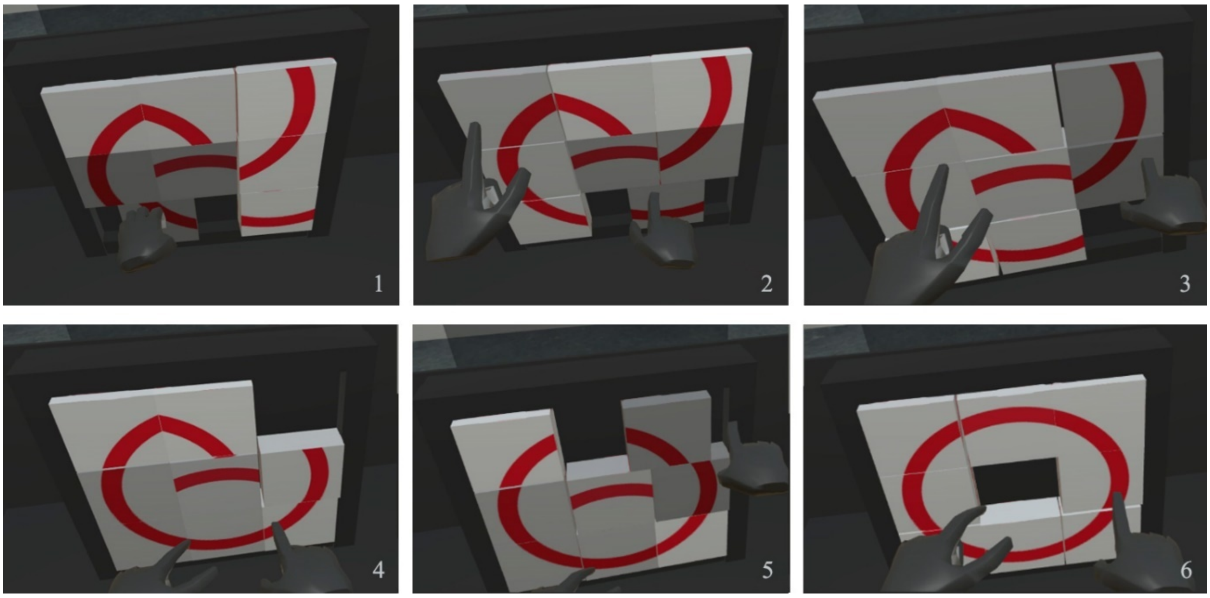
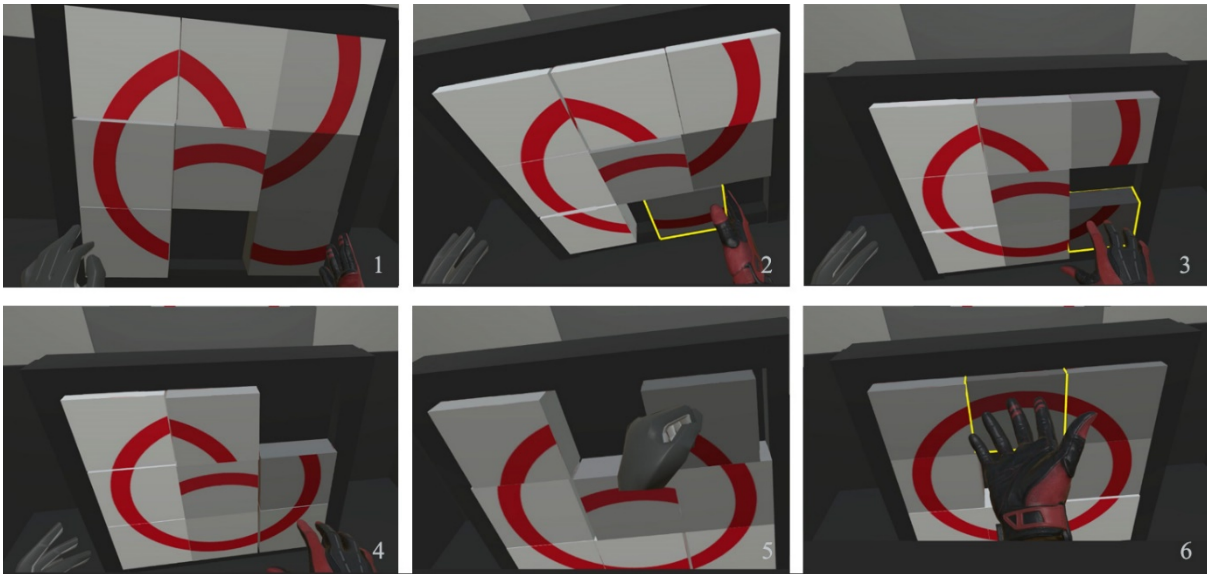


Figure 31 *Puzzle 1 in Mixed Interaction Mode*



4.1.4.2 Wood Block Tower Puzzle

Figures 32, 33, and 34 show the image sequences of Puzzle 2 during the user study. In these figures, participants were asked to complete the wood block tower puzzle using different interaction modes: a) controller-based mode, which was attached to a gloved hand (Figure 32); b) Hand gesture mode, which was attached to a low-polygon hand (Figure 33); and c) mixed interaction mode (Figure 34).

The overall size of the wood block tower puzzle is 21 cm x 21 cm. Participants were required to stack each wood block until it formed a tower. Puzzle 2 and Puzzle 3 included a reset function, where the button on the top allows participants to reset the puzzle if they accidentally drop a wood block out of a reachable area, such as behind the table or wall. Puzzle 1, a sliding puzzle, did not require a reset button, as the pieces do not fall off.

Figure 32 *Puzzle 2 in Controller-based Mode*

Figure 33 *Puzzle 2 in Hand Gesture Mode*

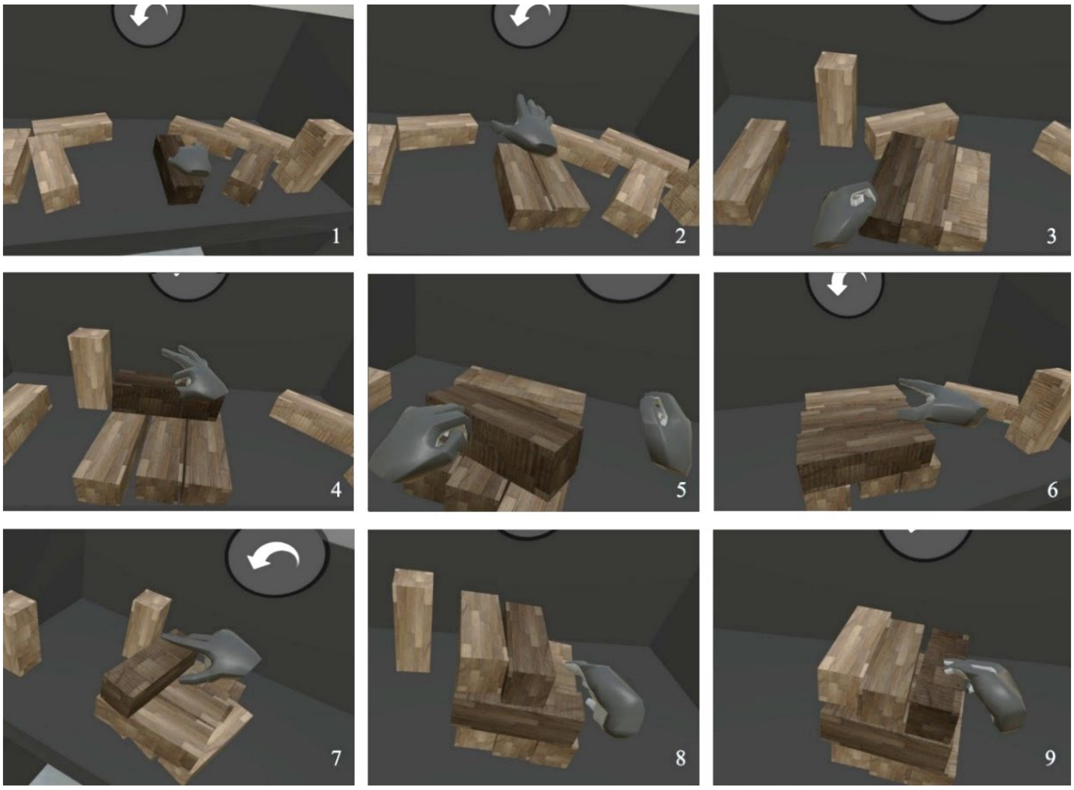
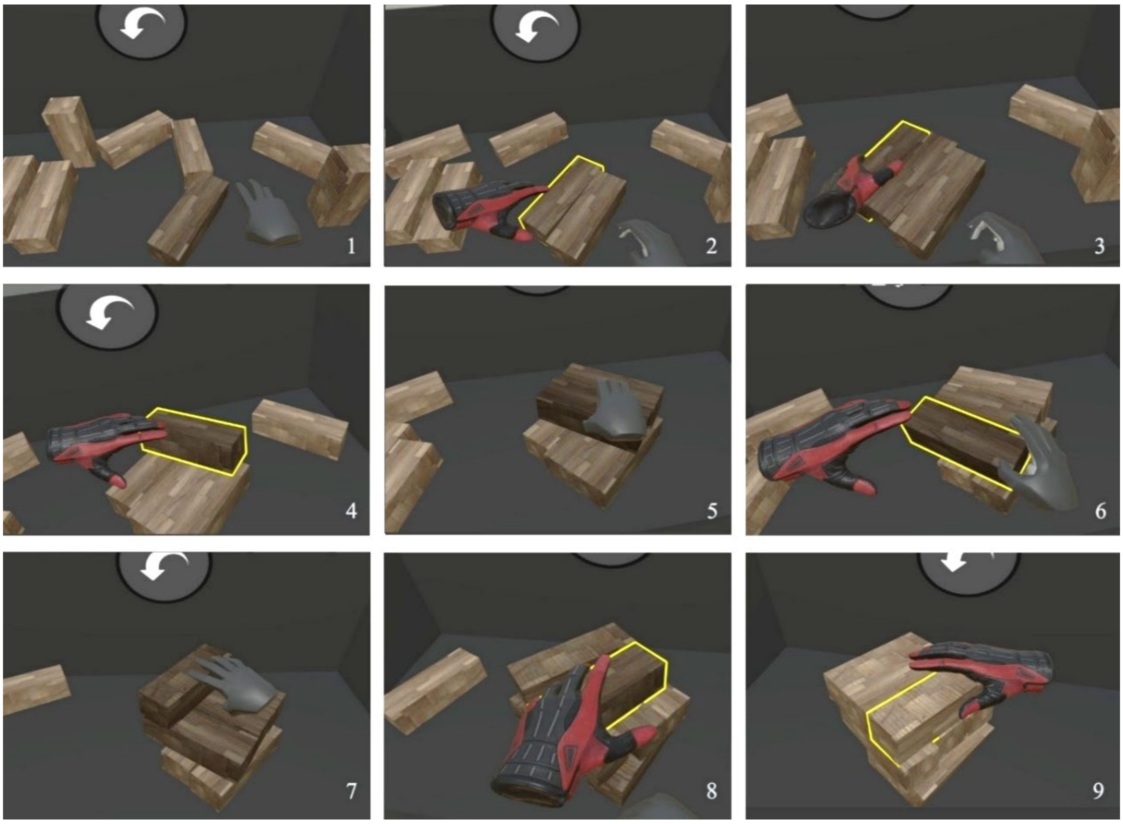


Figure 34 *Puzzle 2 in Mixed Interaction Mode*



4.1.4.3 Interlocking Puzzle

Figures 35, 36, and 37 show the image sequences of Puzzle 3 during the user study. In these figures, participants were asked to complete the interlocking puzzle using different interaction modes: a) controller-based mode, which was attached to a gloved hand (Figure 35); b) Hand gesture mode, which was attached to a low-polygon hand (Figure 36); and c) mixed interaction mode (Figure 37).

The overall size of the interlocking puzzle is also 21 cm x 21 cm. Participants were required to manipulate each wood block until it formed a cube. The button on the top allows participants to reset the puzzle when they accidentally drop a wood block.

Figure 35 *Puzzle 3 in Controller-based Mode*

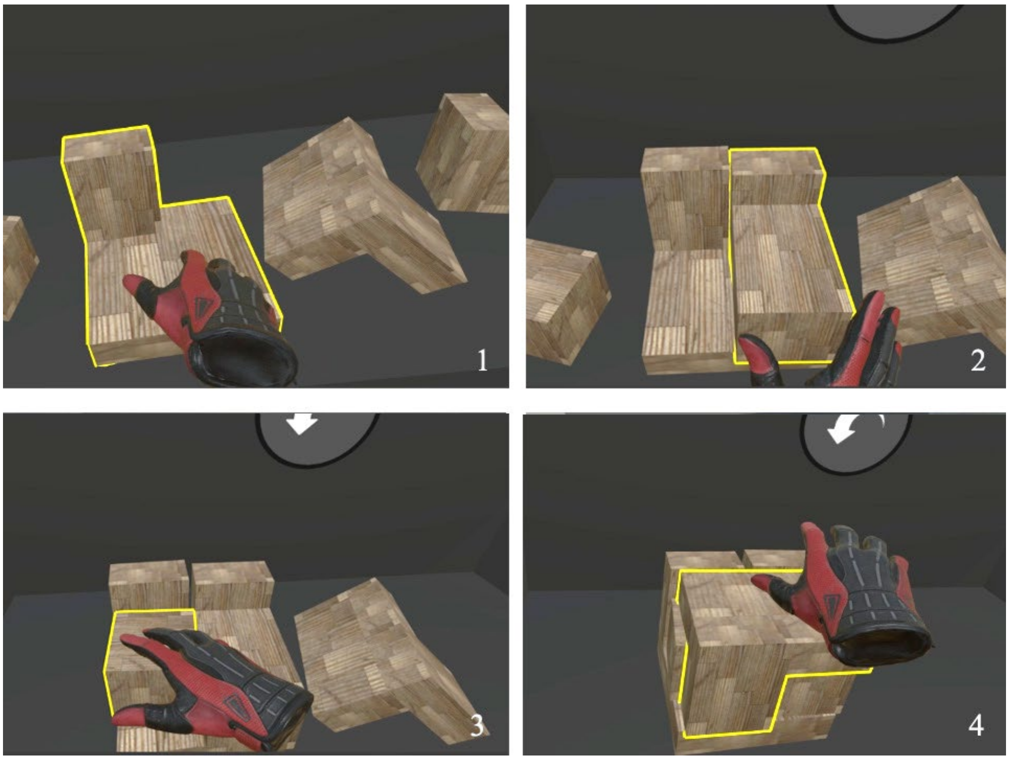


Figure 36 *Puzzle 3 in Hand Gesture Mode*

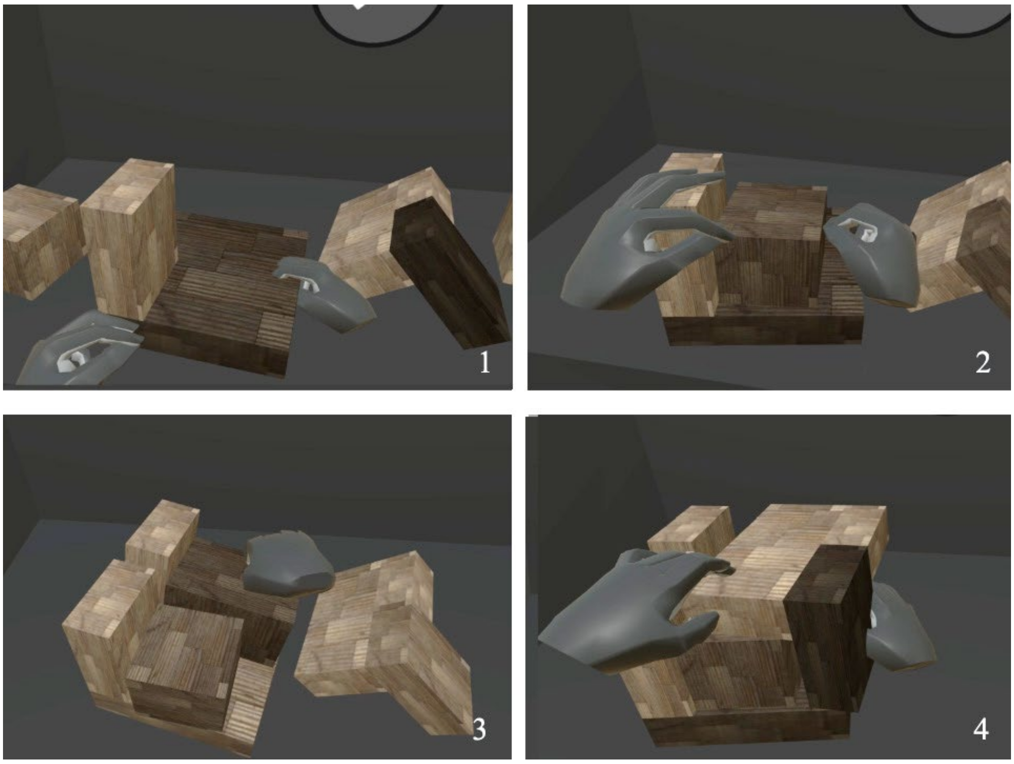
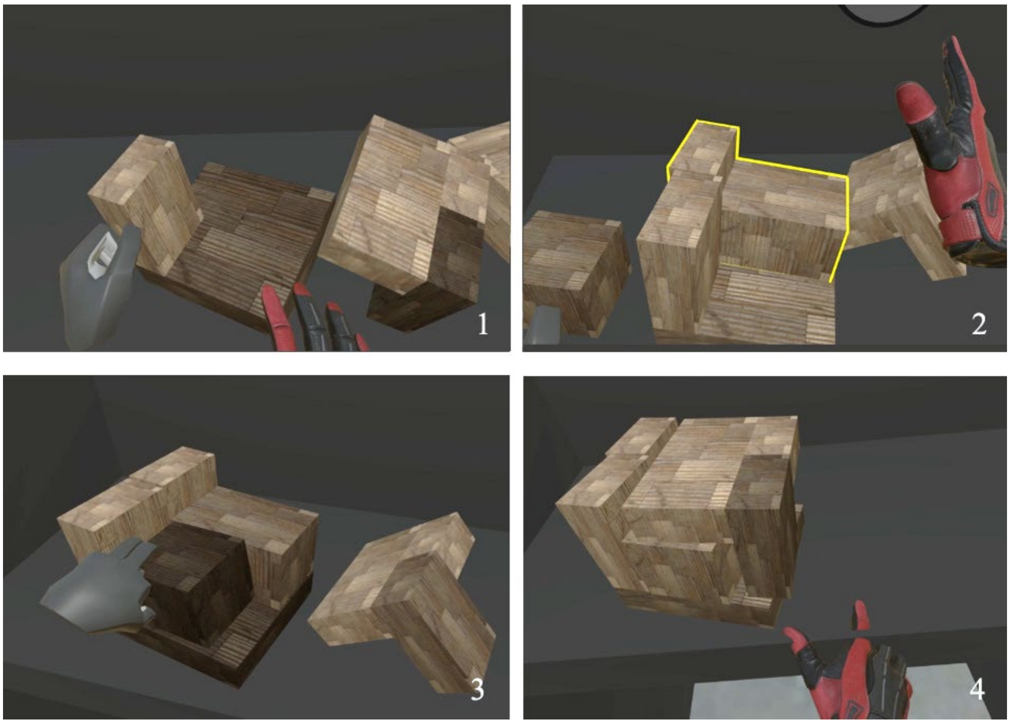


Figure 37 *Puzzle 3 in Mixed Interaction Mode*



4.1.5 Participants

The user study involved 40 randomly recruited participants. All participants were required to attend a 30-minute session at the university campus and no dropouts were reported. Invitations were emailed, and posters were displayed at the AUT campus. Once the potential participants scanned the QR code from the poster, they were directed to the research participation invitation Google form for registration. After registration was completed, a notification was sent. An email with the project outline was then sent to the registrant, which allowed them to decide whether to participate in the user study. This email included the participation information sheet with further research details. On the participant information sheet, the participants were informed that they were free to withdraw from the research at any time without disadvantage. Discomfort and risk were also mentioned on the participant information sheet, as there might be a possibility that some people may not feel comfortable with VR devices. Participants were advised to stop immediately if they experienced physical discomfort during the user study. The VR headset was sanitised with a disinfectant spray after each user study to meet health and safety standards. Before participating, each participant was given a consent form respectively, and all data collection remained anonymous. Although details like age, gender, background, and handedness were not collected, such data could provide valuable insights. Future studies should consider this to improve the study's relevance and fairness. This study was conducted in accordance with ethical guidelines and received approval from the Auckland University of Technology Ethics Committee (AUTEC) on 13 June 2022, with AUTEC Reference number 22/149.

4.1.6 User Tasks

To address the research question, physical and virtual prototypes were developed and tested using three interaction modes: controller-based, hand gesture, and the mixed interaction mode. The physical prototype provided real-world behaviour data, while the VR prototypes facilitated the study of user experience in a virtual environment. The study design incorporated tasks of increasing complexity, allowing participants to progress from basic familiarisation to more demanding interactions, ensuring a comprehensive evaluation of each interface's performance and usability.

Table 4 presents the sequence of prototypes used in the study, which was consistent for all participants, starting with the physical puzzle, followed by the controller-based, hand gesture, and finally the mixed interaction mode. This consistency could lead to participants becoming more proficient over time due to repeated exposure to the technology. This proficiency, however, might not be solely due to the effectiveness of the interaction modes, but rather a result of practice. This is a known limitation of the study design and was factored into the data interpretation.

The study design did not include counterbalancing, which was a limitation of the study. Although changing the puzzle order between participants could have addressed potential task order effects, this was not implemented for two reasons. First, the small sample size limited the statistical power to detect task order effects. Second, switching interaction modes for the same puzzle and repeating tasks could have been disruptive and confusing for participants. Future research could benefit from implementing counterbalancing to reduce such effects. As previously noted, physical models of the puzzles were used to reduce cognitive load, ensuring that any variation in task performance is related to the interaction mode in use.

Table 4 *Puzzle Study Task List*

Prototype and Sequence	*Interaction Mode*			
	Hands	Controller-based	Hand Gesture	Mixed Interaction
1. Physical sliding puzzle	*			
2. Physical wood block tower puzzle	*			
3. Physical interlocking puzzle	*			
4. VR sliding puzzle		*		
5. VR wood block tower puzzle		*		
6. VR interlocking puzzle		*		
7. VR sliding puzzle			*	
8. VR wood block tower puzzle			*	
9. VR interlocking puzzle			*	
10. VR sliding puzzle				*
11. VR wood block tower puzzle				*
12. VR interlocking puzzle				*

Before the main tasks, participants underwent a training phase to familiarise themselves with the manipulation tasks using both the controller-based and hand gesture modes. This training phase lasted approximately 5 minutes, during which participants were given the opportunity to try out the controller-based and hand gesture modes. They practised selecting a puzzle and picking up a woodblock, which are fundamental interactions for the subsequent tasks. Participants were instructed to complete the tasks based on the hints provided in the virtual environment, rather than focusing on speed.

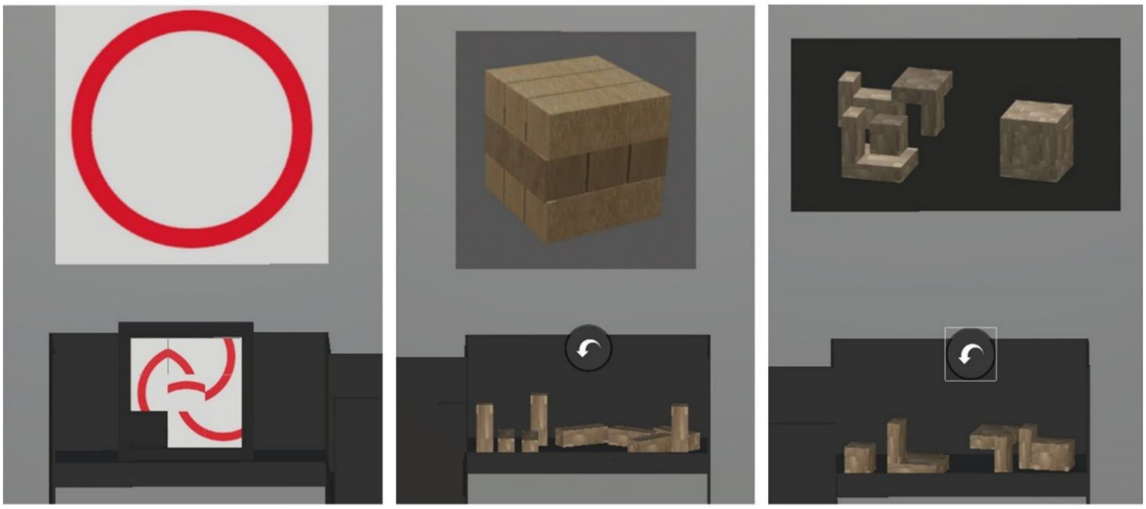
All participants underwent this training phase. The duration was kept consistent to ensure fairness and reduce variability in the data. There was no specific threshold of mastery that participants were required to reach before starting the actual conditions. Instead, the focus was on familiarisation with the technology and the basic tasks. Any potential effects of varying levels of familiarity were considered during the data analysis. However, conducting the training phase in the same environment as the main tasks could introduce a learning effect, which is a limitation of the study. Future studies could use a separate training environment to minimise such effects.

After this training phase, they proceeded to complete three puzzle-based activities as seen in Figure 38, the activities included a) the sliding puzzle, b) the wood block tower, and c) the interlocking wood block puzzle. The three puzzles used in the study were designed to cover a range of interactions, from simple to complex.

1. **The Sliding Puzzle**: This puzzle involved moving pieces within a confined space to form a specific pattern. It allowed for the measurement of how participants adapted to the interface while solving a relatively simple task.
2. **The Wood Block Tower**: This puzzle required stacking blocks to construct a tower. While it might seem trivial, it was designed to test the precision and stability of the interfaces. The simplicity of the task allowed for focus on the physical interactions rather than problem-solving skills.
3. **The Interlocking Wood Block Puzzle**: This was a more complex task that involved manipulating multiple blocks to form a cube. It required a higher level of interaction and the irregular shapes of the blocks added an additional layer of challenge.

While the time measurements for the Sliding Puzzle and the Interlocking Wood Block Puzzle might be influenced by learning effects, the simplicity of the Wood Block Tower puzzle minimises this influence, providing a more direct measure of the effectiveness of the interfaces. It is important to note that the aim was not to measure problem-solving skills, but rather to evaluate the effectiveness of the interfaces across a range of tasks. For all participants and across all interaction modes, each puzzle started from the same position. The puzzles required a range of interactions, from simple sliding to complex multi-object manipulation.

Figure 38 *Puzzles in a Virtual Environment*



a) Sliding puzzle b) Wood block tower puzzle c) Interlocking puzzle

4.1.7 Summary

This section details the design and implementation of the tasks for the first study undertaken to meet the research objective of gathering valuable user study data. The initial phase focused on understanding the characteristics of the controller-based and hand gesture modes, leading to the design of interaction tasks in the final prototype.

The puzzle study was conducted to gain insights into user experience and preferences for different VR interaction modes. These insights informed the development of the cockpit study prototype discussed in the next chapter. Participants were encouraged to verbalise their thoughts during the tasks in a specially designed virtual environment. This approach facilitated data collection and ensured respectful and responsive support for the participants.

Data on task completion time was collected through a data logger, and post-study questionnaires captured user experience. The findings from these studies will contribute to the knowledge of VR object manipulation design guidelines by assessing the suitability of the interaction tasks in a virtual environment. The next section will discuss both quantitative and qualitative data findings.

4.2 Results

The puzzle study employed a convergent design to collect and analyse both quantitative and qualitative data. The analysis was conducted using the JASP software, an open-source software package that is comparable with SPSS (Version 0.18.3; JASP Team, 2024). This section presents an analysis of participant behaviour in the physical puzzle setting. It includes descriptive statistics, results of a normality test, and findings from post hoc tests to identify differences in task completion time and reset counts between groups. Additionally, it reports on the results of questionnaires based on the System Usability Scale (SUS) and NASA Task Load Index (TLX).

4.2.1 Participant Use of Hand(s) Measures

For Puzzle 1, as shown in Table 5, both hands were used by 68% of participants in the physical puzzle, 60% with a controller-based, and 55% with hand gesture. In the mixed interaction mode, both hands were used by 78% of participants, which is the most among all four modes. For Puzzle 2, all participants used both hands in the physical puzzle, and this was closely mirrored in the mixed interaction mode, where 93% of participants used both hands. Lastly, in Puzzle 3, both hands were used by 98% of participants to manipulate the interlocking puzzle when using the physical puzzle. The mixed interaction mode saw a similar trend with 78% of participants using both hands, a figure comparable to the other two interaction modes (further data in Appendix 4).

Table 5 *Use of Hand(s) Analysis*

	Physical	**Controller-based**	**Hand gesture**	**Mixed**
Puzzle 1	1 hand: 32% 2 hands: 68%	1 hand: 40% 2 hands: 60%	1 hand: 45% 2 hands: 55%	1 hand: 22% 2 hands: 78%
Puzzle 2	1 hand: 0% 2 hands: 100%	1 hand: 25% 2 hands: 75%	1 hand: 20% 2 hands: 80%	1 hand: 7% 2 hands: 93%
Puzzle 3	1 hand: 2% 2 hands: 98%	1 hand: 30% 2 hands: 70%	1 hand: 27% 2 hands: 73%	1 hand: 22% 2 hands: 78%

4.2.2 Task Completion Time

The task completion time data were recorded using screen recording (Appendix 1), and the reset count (Appendix 5) in Puzzle 2 and Puzzle 3 was captured using the data logger function created in Unity 3D.

4.2.2.1 Normality Analysis

Quantile-quantile plots were used to assess whether a dataset follows a specific probability distribution (Appendix 6). The results of the data analysis indicated that the dataset was non-normally distributed in Appendix 11, as the Shapiro-Wilk test yielded a significance level (*p*-value) of less than 0.05 (Hartwig & Dearing, 1979). Therefore, non-parametric tests were deemed more appropriate for analysing the data. Levene's Test was used to check the homogeneity of variances in the datasets (Table 6). The test results indicated a significance level of less than $p < .05$.

Table 6 *Levene's Test: Homogeneity of Variances for Task Completion Time*

Puzzle 1

type	*p*-value
medians	0.0045

Puzzle 2

type	*p*-value
medians	0.021

Puzzle 3

type	*p*-value
medians	0.012

The Friedman test was chosen to analyse the data. The Friedman test is considered robust when applied to non-normally distributed data (Rigas et al., 2018). The decision to use the Friedman test in the analysis is also based on the structure of the study, where each participant experiences all conditions. This differs from the Kruskal-Wallis test, which is more suited for studies where different groups of participants experience different conditions. This adjustment in the statistical approach aligns better with the data distribution in this study.

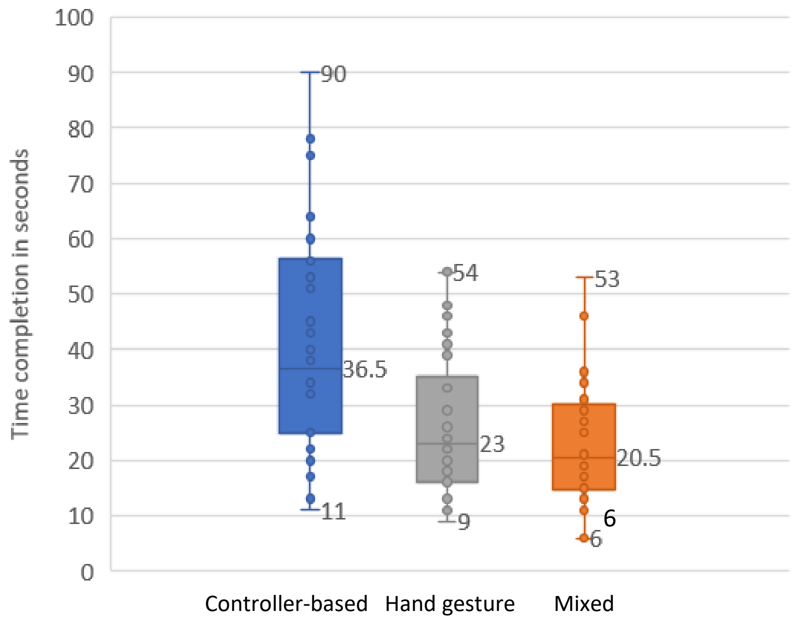
4.2.2.2 Post hoc Analysis

As detailed in Appendix 2, the Friedman test was used to identify any statistically significant differences among the three interaction modes based on user responses. This test is suitable for ordinal data and does not require a normal distribution (Beasley & Zumbo, 2003). Following the Friedman test, a post hoc Conover test was performed to determine significant differences (Appendix 3). For the Conover test, a Bonferroni correction was applied by adjusting the p-value (p-bonf). This adjustment involves multiplying the p-value by the number of comparisons (n) (Weisstein, 2004). In this case, with 3 tests, the adjusted significance level was evaluated using $p\text{-bonf} < 0.05$. The adjusted p-value (p-bonf) is always three times the original p-value, ensuring that if p-bonf is less than the alpha value (0.05), the result is considered significant. When reporting these results, the Friedman Test p-values are presented directly, whereas post hoc tests apply the Bonferroni correction to the p-values (p-bonf) to account for multiple comparisons.

4.2.2.3 Puzzle 1 Task Completion Time and Performances

The following results are shown in box and whisker graphs, the comparative analysis centres on comparing task completion time with each interaction mode across the three puzzles. In Puzzle 1 (Figure 39), the range and the interquartile range of mixed interaction mode are the narrowest among the two interaction modes, indicating the participants' performance was more stable during the mixed interaction mode. The mixed interaction mode shows the best median in task completion time among the two interaction modes. Moreover, the shortest task completion time (6 seconds) is recorded in the mixed interaction mode in Puzzle 1. In contrast, the longest task completion time (90 seconds) and the widest range and interquartile range are noted in controller-based mode.

Figure 39 *Participant Task Completion Time in Puzzle 1*



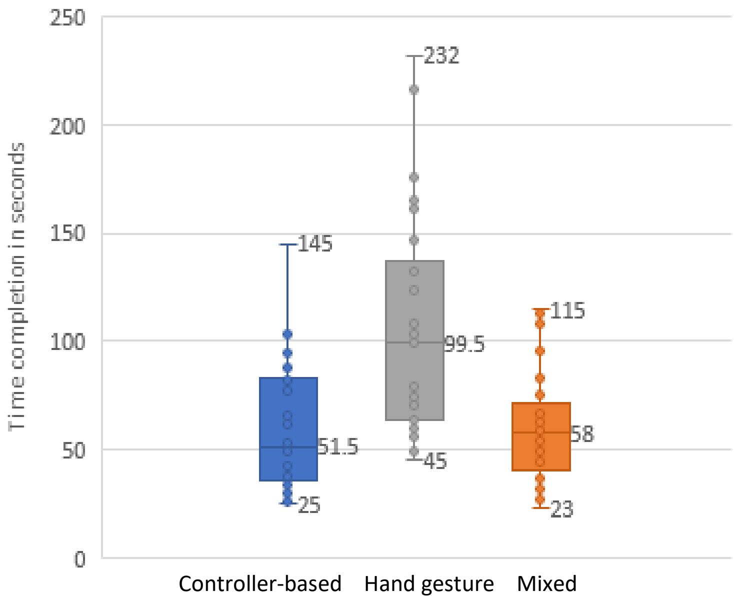
The Friedman Test was conducted to compare the task completion time from Puzzle 1 across three interaction modes. The test results are as follows: an alpha level of 0.05, a Q-statistic of 17.478, and 2 degrees of freedom. The task completion time from Puzzle 1 across three interaction modes revealed a significant difference ($p < 0.001$).

Post hoc tests for task completion time across controller-based, hand gesture, and mixed interaction modes revealed significant differences. The results showed significant differences between controller-based and hand gesture (p-bonf < 0.001), and controller-based and mixed (p-bonf < 0.001). However, hand gesture and the mixed interaction mode were not significantly different.

4.2.2.4 Puzzle 2 Task Completion Time and Performance

The following box and whisker graph in Figure 40 shows the task completion time results for Puzzle 2. The range and the interquartile range of mixed interaction mode are the narrowest among the two interaction modes, indicating the participants' performance was more stable during the mixed interaction mode. Also, the shortest task completion time (23 seconds) is recorded in the mixed interaction mode, whereas the longest task completion time is recorded in hand gesture mode (232 seconds). The range and the interquartile range of hand gesture are broader and higher than those of the other modes, which means the task performance varied among the participants during the user study.

Figure 40 *Participant Task Completion Time in Puzzle 2*



The Friedman Test was conducted to compare the task completion time from Puzzle 2 across three interaction modes. The test results are as follows: an alpha level of 0.05, a Q-statistic of 30.730, and 2 degrees of freedom. The task completion time from Puzzle 2 across three interaction modes revealed a significant difference ($p < 0.001$).

Post hoc tests for task completion time across controller-based, hand gesture, and mixed interaction modes for Puzzle 2 revealed significant differences. The results showed significant differences between controller-based and hand gesture (p-bonf < 0.001), and hand gesture and Mixed (p-bonf < 0.001). However, controller-based and mixed were not significantly different.

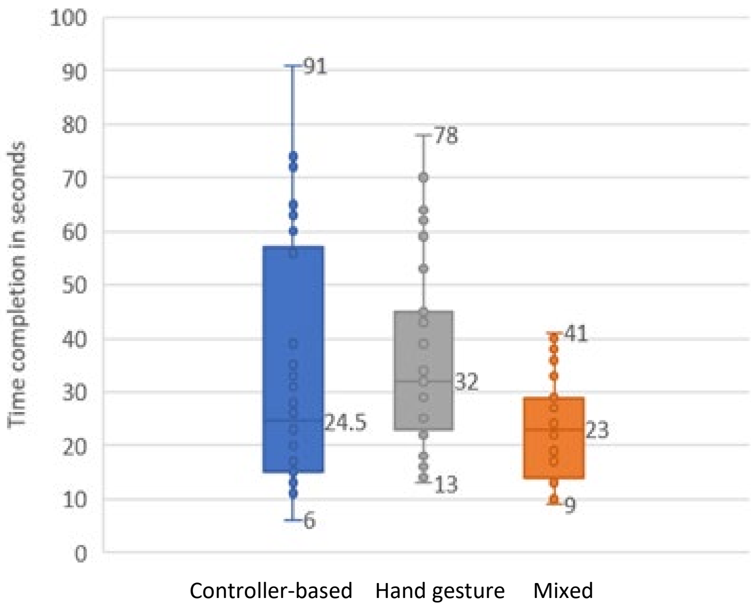
<u>Reset Count</u>

In Puzzle 2, resets were recorded each time participants pressed the reset button, which also reset the task timer. Appendix 5 details that resets occurred 11 times in controller-based mode, 15 times in hand gesture mode, and 11 times in mixed interaction mode, with hand gesture mode showing a marginally higher number of attempts. Only the time of the successful attempt was measured, ensuring that the data reflects the final completion rather than the total time spent, including resets. This means that while the reset data provides insight into the number of attempts, the measured task completion times focus solely on the successful completion. A more detailed breakdown, including individual attempts, has been moved to the appendix for clarity.

4.2.2.5 Puzzle 3 Task Completion Time and Performance

The following box and whisker graph in Figure 41 shows the task completion time results in Puzzle 3. The range and the interquartile range of the mixed interaction mode are the narrowest and faster than the other two interaction modes, indicating the participants' performance was more stable during the mixed interaction mode. The interquartile range of the controller-based is wider than the other modes, and the task performance is not as stable as the other modes during the user study. However, the shortest task completion time (6 seconds) is recorded in controller-based mode, and the longest task completion time is also recorded in controller-based mode (91 seconds).

Figure 41 *Participant Task Completion Time in Puzzle 3*



The Friedman Test was conducted to compare the task completion time from Puzzle 3 across three interaction modes. The test results are as follows: an alpha level of 0.05, a Q-statistic of 8.316, and 2 degrees of freedom. The task completion time from Puzzle 3 across three interaction modes revealed a significant difference (p = 0.0156).

Post hoc tests for task completion time across controller-based, hand gesture, and mixed interaction modes for Puzzle 3 revealed mixed results. The Conover test found significant differences only between hand gesture and mixed (p-bonf = 0.0016), but no significant differences between controller-based and hand gesture, and controller-based and mixed.

Reset Count

In Puzzle 3, the number of resets was recorded, which occurred when participants pressed the reset button during the user study. As detailed in Appendix 5, the total count of resets for Puzzle 3 was 3 times in controller-based mode, 18 times in hand gesture mode, and 5 times in mixed interaction mode. It was observed that the hand gesture mode saw a higher number of attempts. A more detailed breakdown of the data, including individual attempts, has been moved to the appendix for clarity.

4.2.3 Questionnaire

After completing all the interaction tasks, participants were asked to fill out a modified usability questionnaire inspired by the SUS and TLX frameworks (Brooke, 2013; Lewis, 2018), as detailed in Appendix 7. The modified questionnaire was designed to evaluate user satisfaction and usability during usability evaluations. Unlike the standard SUS, which typically provides a single usability score, this study aimed to gain a more detailed understanding by analysing individual questions. This approach creates a new questionnaire, which may not produce results directly comparable with standard SUS scores due to its unique structure. As previously noted, variations from established norms can be accommodated in pragmatic research paradigms, provided they are discussed and explained. The focus on individual questions was chosen to explore the interaction modes in detail, rather than just evaluating the usability of the system as a whole.

This custom approach allowed for a more granular understanding of user experiences. It's important to note that previous research has shown a relatively weak correlation between SUS scores and certain behavioural usability metrics (Drew et al., 2018). To aid in interpreting individual responses, a descriptive rating scale was added, which helps simplify the explanation of findings to those not familiar with human factors (Bangor et al., 2009).

The custom usability questionnaire consisted of 11 questions. The Friedman test was used to identify statistically significant differences in user responses across the three interaction modes (Appendix 8). For questions where a significant difference was identified (at a significance level of $p < 0.05$), a post hoc analysis using the Conover test was conducted (Appendix 9). This was followed by an assessment of user preference in questions 12-13. In the TLX questionnaire (questions 14-18), participants were asked to rate their mental workload on a scale from 1 to 21.

There could be a potential limitation in the participants' responses. As the tasks progressed, participants might have a stronger recollection of their most recent experiences, potentially overshadowing their initial experiences. This could skew the custom questionnaire scores and is a limitation that should be acknowledged. Future studies could consider methods to mitigate this effect, such as providing questionnaires after each task to capture more balanced views of the participants' experiences.

4.2.3.1 Custom Usability Questionnaire

The custom usability questionnaire required participants to rate their responses on a scale from 1 (Strongly Disagree) to 5 (Strongly Agree). It consists of 11 questions and the median scores of the answers are presented in Figure 42.

Figure 42 *Participants' Answers to Question 1 - 11*

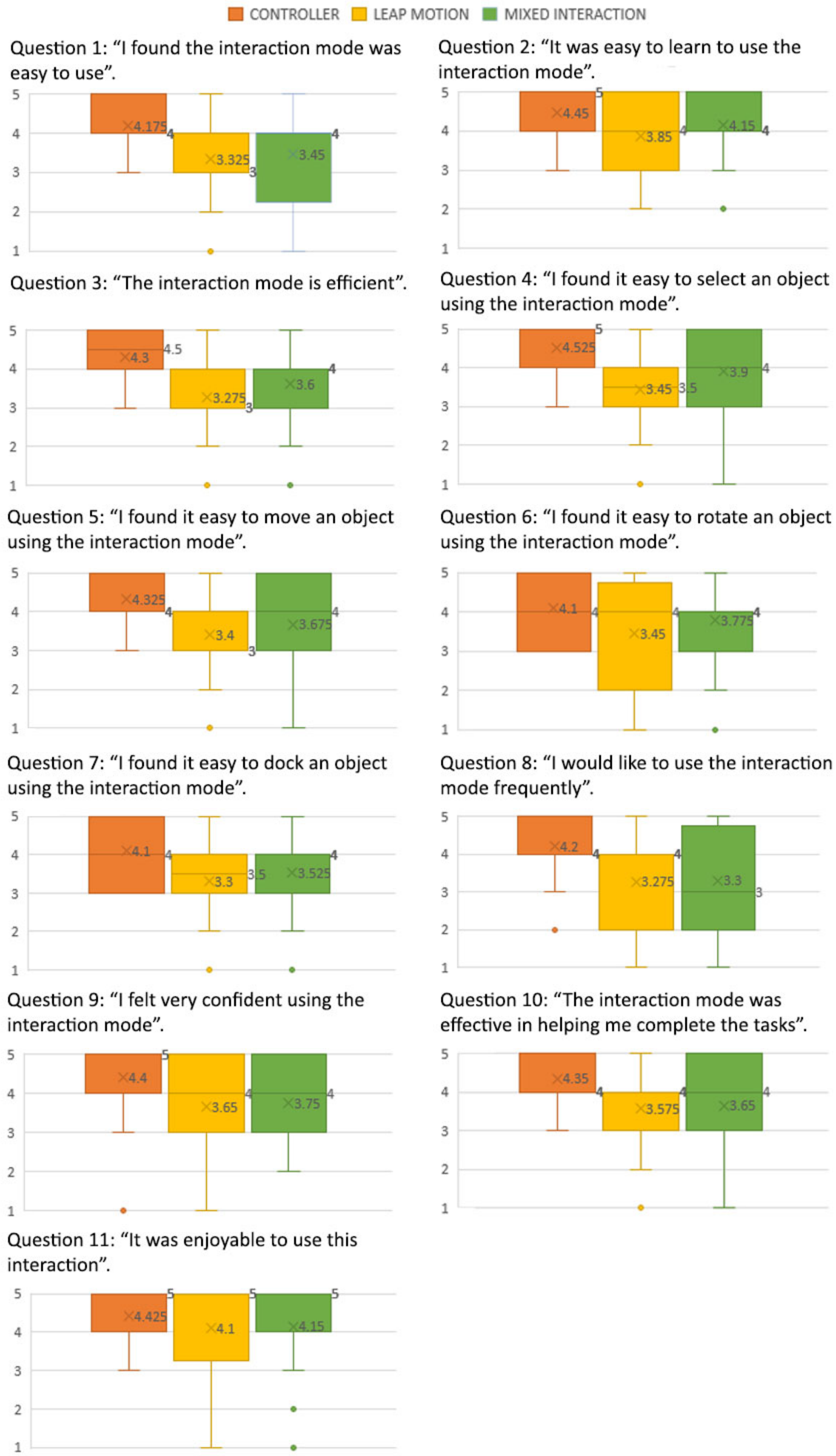


Table 7 shows the median scores for each question and indicates whether there were statistically significant differences between the interaction modes:

Table 7 *Median Scores and Significant Differences for Question 1 – 11*

Question	Controller-based (Median)	Hand gesture (Median)	Mixed (Median)	Significant Differences (Conover test)
1	4	3	4	Controller-based vs Hand gesture, Controller vs Mixed
2	5	4	4	Controller-based vs Hand gesture
3	4.5	3	4	Controller-based vs Hand gesture, Controller-based vs Mixed
4	5	3.5	4	Controller-based vs Hand gesture, Controller-based vs Mixed
5	4	3	4	Controller-based vs Hand gesture, Controller-based vs Mixed
6	4	4	4	Not applicable
7	4	3.5	4	Controller-based vs Hand gesture, Controller-based vs Mixed
8	4	4	3	Controller-based vs Hand gesture, Controller-based vs Mixed
9	5	4	4	Controller-based vs Hand gesture, Controller-based vs Mixed
10	4	4	4	Controller-based vs Hand gesture, Controller-based vs Mixed
11	5	5	5	Not applicable

In summary, the controller-based mode was generally perceived as easier to use and learn, with higher median scores in these areas compared to the hand gesture mode. However, the introduction of mixed interaction mode did not significantly alter participants' ratings of ease of use or learning. This result echoes the results from a previous study (Lee et al., 2020), where subjective opinions differed from the objective data.

Interestingly, no significant differences were found in the responses to the questions about the enjoyment of using the interaction modes (Question 11) and the ease of rotating an object (Question 6), indicating similar levels of enjoyment and ease of rotation across all three modes. For other tasks such as object selection (Question 4), object movement (Question 5), and object docking (Question 7), the controller-based mode was found to be significantly easier compared to the hand gesture mode. Participants also indicated a preference for using the controller-based mode more frequently

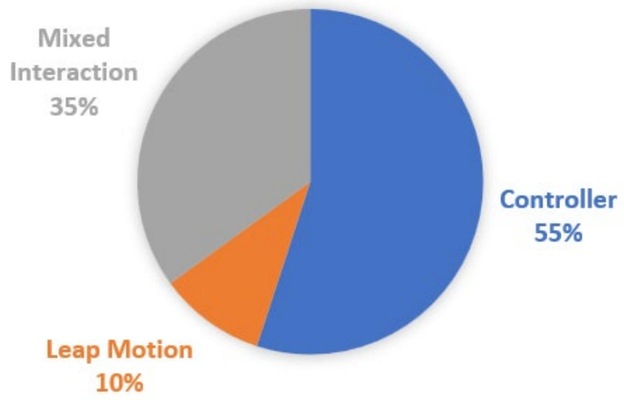
(Question 8) and felt more confident using it (Question 9). For the task of object manipulation effectiveness (Question 10), the controller-based mode was only found to be significantly more effective than the hand gesture mode, but not the mixed interaction mode. The detailed findings will be further discussed in Chapter 6.

4.2.3.2 User Preference Questionnaire

In Figure 43, for the tasks the participants were asked to do, statistics show that 55% of participants prefer the controller, 35% prefer the mixed interaction mode, and 10% prefer the hand gesture.

Question 12: For the tasks I was asked to do, I prefer this interaction mode the most.

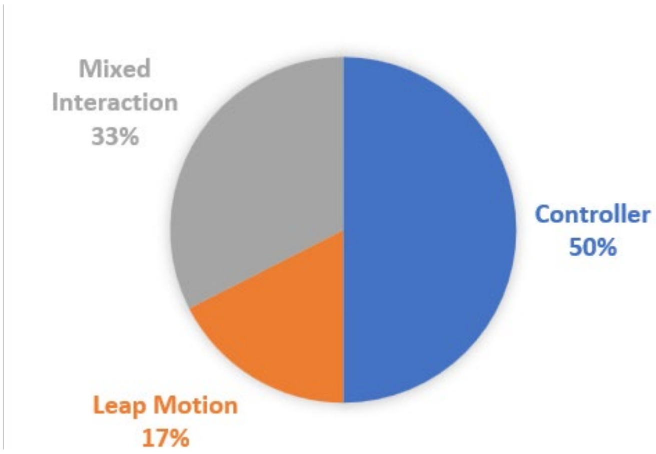
Figure 43 *Participants' Preferences in Question 12*



In Figure 44, statistics show that 50% of participants prefer the controller-based mode, 33% prefer the mixed interaction mode, and 17% prefer the hand gesture mode.

Question 13: Overall, I prefer this interaction mode the most.

Figure 44 *Participants' Preference in Question 13*



In summary, the results indicate a preference among participants for using a controller-based rather than a hand gesture or mixed interaction mode for completing tasks. This suggests that users may find the controller-based more straightforward when completing tasks.

4.2.3.3 TLX Questionnaire

For questions 14 to 18, the participants were asked to rate the mental workload on a scale from 1 to 21 (Appendix 7). The Friedman test was employed to identify any statistically significant differences in user responses across the three interaction modes (Appendix 8), a subsequent post hoc test was carried out, as outlined in Appendix 9. The TLX questionnaire required participants to rate their mental workload on a scale from 1 to 21. It consists of 5 questions and the median scores of the answers are presented in Figure 45.

The questionnaire included the following questions:

Question 14:

> "How mentally demanding was the task?". Participants would provide answers ranging from 1 for "Very low" to 10 for "Average" to 21 for "Very High".

Question 15:

> "How physically demanding was the task?". Participants would provide answers ranging from 1 for "Very low" to 10 for "Average" to 21 for "Very High".

Question 16:

> "How successful were you in accomplishing what you were asked to do?". Participants would provide answers ranging from 1 for "Perfect" to 10 for "Average" to 21 for "Failure".

Question 17:

> "How hard did you have to work to accomplish your level of performance?".
> Participants would provide answers ranging from 1 for "Very low" to 10 for "Average" to 21 for "Very High".

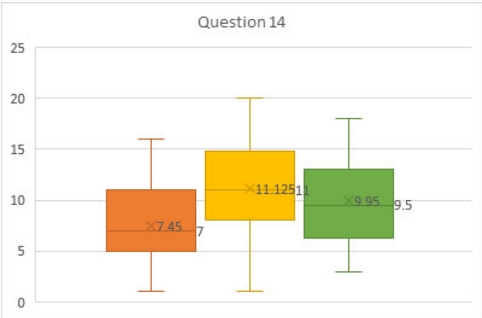
Question 18:

> "How insecure, discouraged, irritated, stressed, and annoyed were you?". Participants would provide answers ranging from 1 for "Very low" to 10 for "Average" to 21 for "Very High".

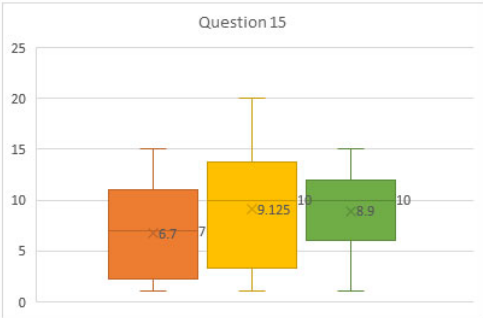
Figure 45 *Participants' Answers to Question 14 – 18*

CONTROLLER LEAP MOTION MIXED INTERACTION

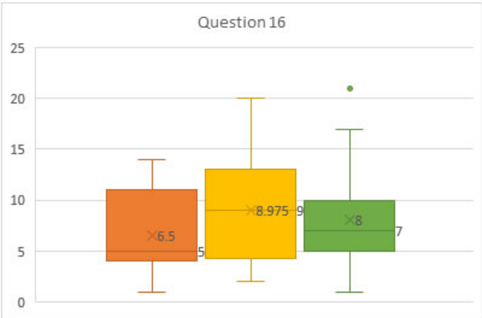
Question 14: "How mentally demanding was the task?".



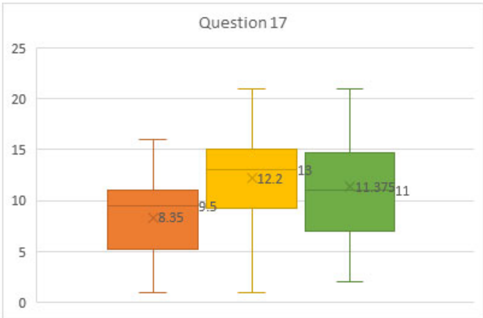
Question 15: "How physically demanding was the task?".



Question 16: "How successful were you in accomplishing what you were asked to do?".



Question 17: "How hard did you have to work to accomplish your level of performance?".



Question 18: "How insecure, discouraged, irritated, stressed, and annoyed were you?".

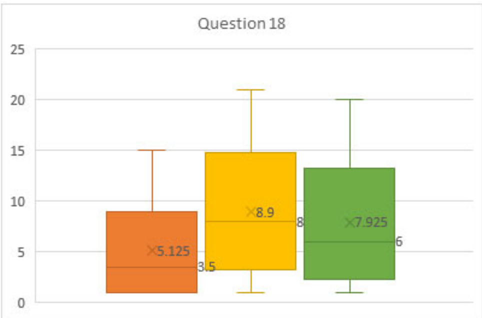


Table 8 shows the median scores for each question and whether there were statistically significant differences between the interaction modes:

Table 8 *Median Scores and Significant Differences for Question 14 – 18*

Question	Controller-based (Median)	Hand gesture (Median)	Mixed (Median)	Significant Differences (Conover test)
14	7	11	9.5	Controller-based vs Hand gesture, Controller-based vs Mixed
15	7	10	10	Controller-based vs Hand gesture, Controller-based vs Mixed
16	5	9	7	Controller-based vs Hand gesture
17	9.5	13	11	Controller-based vs Hand gesture, Controller-based vs Mixed
18	3.5	8	6	Controller-based vs Hand gesture, Controller-based vs Mixed

In summary, the TLX questionnaire findings revealed the following key insights:

For the question on mental demand (Question 14), the controller-based mode was found to be less mentally demanding (Median: 7) compared to the hand gesture (Median: 11) and mixed interaction mode (Median: 9.5). This difference was statistically significant.

For the question on physical demand (Question 15), the Conover test indicates a significant difference between the controller-based and hand gesture modes, and between the controller-based and mixed interaction modes.

For the question on success in task accomplishment (Question 16), the controller-based mode was found to be significantly more successful than the hand gesture mode.

For the question on effort to achieve performance (Question 17), the controller-based mode was found to be significantly less effortful compared to the hand gesture and mixed interaction modes.

Finally, for the question on negative feelings (Question 18), the controller-based mode was found to be significantly less associated with negative feelings compared to the hand gesture and mixed interaction modes. The detailed findings will be further discussed in Chapter 6.

4.2.4 Talk-aloud Verbal Summary

The primary role of the participants is to share their preferences for different interaction modes in VR. The purpose of notetaking is to capture participants' comments to remind the observer about the activities, and the field notes require accuracy and no bias (Yates & Leggett, 2016, p.226). The user experience provided opportunities to review the advantages and disadvantages of these applications and the natural interactions with the participants. Table 9 contains verbal data that provided valuable suggestions for further development in the cockpit study. All comments are included in Appendix 12.

The triangulation of participants' verbal feedback with their task completion times and reset frequencies offers valuable insights into their preferences and performance across different interaction modes. Each participant's experiences with the controller-based, hand gesture, and mixed interaction modes reveal both consistencies and variations that highlight the strengths and limitations of each approach.

Participants who favoured the controller often cited its stability and ease for grasping and placing objects, which corresponded with their task performance. For instance, Participants 13 and 14 noted the controller's reliability for secure placements, and both demonstrated faster completion times for these tasks using the controller, particularly in Puzzle 3, where Participant 13 achieved their quickest time with this mode. Conversely, tasks involving rotation and finer adjustments were often quicker with hand gesture mode, aligning with comments from Participants 3 and 14, who observed that hand gesture mode allowed smoother rotations. This alignment was especially clear in tasks such as Puzzle 3, where Participant 3 completed the puzzle more rapidly with hand gesture compared to other modes.

The mixed interaction mode, while perceived by some as requiring more practice, showed promise as a balanced option for complex tasks. Participant 24, who described the mode as "intuitive," showed consistently fast completion times with mixed interaction, including a notably efficient time in Puzzle 1. Similarly, Participant 27 found mixed interaction mode engaging but acknowledged the need for acclimation to its demands. Participant 30 expressed concerns related to physical strain, particularly with the controller. Although tis comment indicated the impact of controller weight on task endurance, it did not reflect in the task completion times. Additionally, this participant took a long time to complete tasks using the hand gesture mode and required more reset time.

Another recurring theme was the lack of physical feedback with hand gesture mode, which some participants found unfamiliar. Participant 8 completed tasks relatively quickly despite this challenge, indicating an adaptability to hand gesture mode. Participant 17's comment on the controller's weight impacting task performance also aligned with the performance data. This participant achieved faster times with the mixed interaction mode for tasks requiring sustained precision, suggesting that a lighter interaction option may be advantageous for prolonged tasks.

In some cases, participants preferred a particular mode based on the unique demands of each puzzle. Participant 37, for instance, selected hand gesture mode for sliding tasks and achieved their best time with this choice in Puzzle 1. The adaptability and fluidity of mixed interaction were recognised by Participant 23, who proposed its potential use in applications such as shooting games, where the controller could provide the necessary stability for aiming while hand gesture mode would handle dynamic interactions like reloading.

Table 9 *Verbal Data from the Puzzle Study: Suggestions for Further Development*

PARTICIPANT ID	COMMENTS
3	*"Controller is better in some movements, but some are better with my own hands."*
7	*"I found that a bit easier to have controller in my dominant hand."*
8	*"It's kinda weird of not having anything that you can physically touching (Leap Motion)"*
13	*"Use controller to grasp, use Leap Motion to rotate is quicker."* *"Move object over to another hand with your own hand is easier with leap"*
14	*"Easy to rotate with right hand (Leap Motion) and place an object with controller."*
17	*"With the controller, it always feels heavier."*
19	*"The Leap is easier in puzzle 1, but harder in puzzle 3."*
23	*"Come back with thoughts in mixed interaction, I can see the potential in shooting games, I like shoot game, will be nice to use the controller, like holding a gun with the controller because you need some weight and feel like holding a real gun but load the gun with the Leap"*
24	*"Mixed interaction is very intuitive."*

27	*"Need practice in mixed interaction, it's interesting"*
30	*"The controller is so cool, but I'm tired"* *"Leap Motion is so cool, and I quickly did it."*
34	*"It's hard to slide with a controller."*
37	*"Able to decide which interaction mode to use in the three puzzles, e.g., Leap to slide, mixed for the tower, controller for interlocking puzzle"*

4.2.5 Summary

The puzzle user study conducted on puzzles aimed to explore the user experience of mixed interaction in comparison to the controller-based and hand gesture modes. The intention was to identify the strengths and weaknesses of different interaction modes. The data collected from the study provided insights into participants' behavioural measures, task performance, usability, mental workload, and preferences. It is important to note that these observations are based on aggregate data from all participants, not individual results. This approach helps to account for individual differences and provides a more accurate representation of the overall trends in the data.

Screen recordings were used to gather data on handedness and task completion time. During the user study, participants' behavioural measures were recorded to assess task performance. It was observed that participants' choice of using one hand or both hands during the hand gesture mode varied, which influenced the task completion time across all three puzzles.

A significant proportion of participants used both hands across all puzzles and interaction modes. In particular, the mixed interaction mode saw the highest percentage of participants using both hands for Puzzle 1 and comparable percentages for Puzzles 2 and 3. This suggests that the mixed interaction mode, which combines the use of controller-based and hand gesture interactions, may encourage more natural and intuitive interactions. However, there were also participants who preferred to use only one hand in certain interaction modes. This was particularly evident in the hand gesture mode, where a number of participants opted to use only one hand. This highlights the importance of providing flexible interaction options to accommodate different user preferences and strategies.

In the case of Puzzle 3, the number of resets, which occurred when participants pressed the reset button during the user study, was also recorded. The total count of resets was 3 times in controller-based mode, 18 times in hand gesture mode, and 5 times in mixed interaction mode. It was observed that the hand gesture mode saw a higher number of attempts. The results indicate that task completion time and the number of resets varied depending on the interaction mode used and the specific puzzle. However, the optimal interaction mode is not universal but depends on the specific task and the user's experience and skill level.

On the other hand, participants showed their interest in mixed interaction, and their comments suggest potential ideas to develop further in the cockpit study. Overall, the findings contributed to knowledge and insights into the development of mixed interaction and existing VR interaction literature. Triangulation was used to gain a deeper understanding of the phenomenon through qualitative and quantitative research. To ensure valid and reliable results, qualitative data were triangulated with quantitative data, which was used to gain insight into participant behaviour. This methodology allowed the research to reduce the risk of bias from using a single data source and provided a broader picture of the phenomenon. More details will be discussed in the next section.

4.3 Implications

The original intention of a convergent design was to collect and triangulate quantitative and qualitative data in the puzzle study to understand how users experienced the interaction. The study produced some mixed results and insights, and while there is some potential for the mixed interaction mode to be useful, the data does not present a strong case for its adoption. This was perhaps due to the tasks being relatively generic, so a further study was designed. It was inspired by the talk-aloud verbal data, particularly the comments made by Participant 23, where the user suggested there was potential to adopt mixed interaction mode in a shooting simulator. The intention of the second study, therefore, was to investigate the mixed interaction mode in a scenario that was designed for mixed interaction. With the use of triangulation, the mixed methods research process was then shifted to an explanatory sequential design in two stages, where the results from the puzzle study can be used to develop and inform the design and purpose of the cockpit study (Johnson & Onwuegbuzie, 2004), and interview findings in the cockpit study help to explain the findings from the puzzle study (Bowen, & Pilkington, 2017). According to Glaser and Strauss (2017), in the discussion on theoretical sampling, the process of collecting data for comparative analysis is designed to generate a formal theory. The data can be collected, coded, and analysed jointly and then decided what and where to collect it afterwards to develop the theory as it emerges. After discussing with supervisors, the research shifted focus to developing a new concept for the cockpit study that accounts for the valuable feedback provided.

4.4 Key Insights

The results from the puzzle study serve as a catalyst for further investigation in the cockpit study. This research approach involves data triangulation, which combines multiple datasets, methods, and investigators to enhance the validity and credibility of the findings. Table 10 summarises the key insights from the puzzle study, including quantitative and qualitative findings.

Table 10 *Summary of Puzzle Study Insights*

Triangulation Aspect	Methods	Key Insights
Quantitative Measures	Task completion time	• Mixed interaction mode showed faster median task completion times for puzzle 1 and 3. • Narrowest range and interquartile range in mixed interaction mode.
Qualitative Findings	Talk-aloud verbal data and questionnaires	**Controller-based**: • **Pros**: Easier for grasping and placing objects. • **Cons**: Physically tiring due to weight.
		Hand gesture: • **Pros**: Allows quicker object rotation. • **Cons**: Lower precision compared to the controller.
		Mixed Interaction: • **Pros**: Real-world behaviour alignment, especially for complex tasks. • **Cons**: Requires further development but shows promise.

The Quantitative Measures

The quantitative findings show that mixed interaction mode indicated faster median task completion times for puzzles 1 and 3, which could be partially attributed to the learning effect as participants became more familiar with solving the puzzles. Furthermore, the analysis of task completion times revealed that the range and interquartile range of the mixed interaction mode were the narrowest among the two interaction modes. This indicates that participants' performance was more consistent across the puzzles, particularly in complex tasks requiring real-world behaviour alignment. For puzzle 2, which did not involve learning, the controller-based mode outperformed the mixed interaction mode in terms of task completion time, highlighting that the mixed mode's advantages may be more evident in tasks involving learning and real-world task complexity.

The Qualitative Findings

Participants consistently expressed confidence in using mixed interaction mode, as reflected in their questionnaire responses. However, they also highlighted usability challenges, particularly the weight of the controller. Despite this, the controller demonstrated superior performance in tasks involving grasping and placing objects, while the hand gesture mode excelled in enabling quicker object rotation.

Notably, the results emphasised the importance of clear models and practical examples for personalised learning. Interestingly, existing professional development and external training programs often fell short in addressing specific needs. These insights underscore the significance of tailoring educational approaches to individual requirements and providing tangible applications for effective learning.

Participants highlighted that the mixed interaction mode aligned well with real-world experiences, particularly for complex tasks. While promising, it requires further development. Given the inconclusive results from the puzzle study, particularly regarding the mixed interaction mode’s comparative performance, the subsequent cockpit study was designed to further investigate its applicability in a more complex, real-world environment. This extension aims to provide additional clarity on the performance and potential advantages of the mixed interaction approach in realistic settings.

Chapter 5: The Cockpit Study

This chapter details the process of the cockpit study. Section 5.1 describes the design process, which contains information on participant recruitment, user task setup, and details of the interview protocol process. Section 5.2 presents the user interview results and the data analysis procedures. Finally, a summary of the cockpit study is presented.

5.1 Design

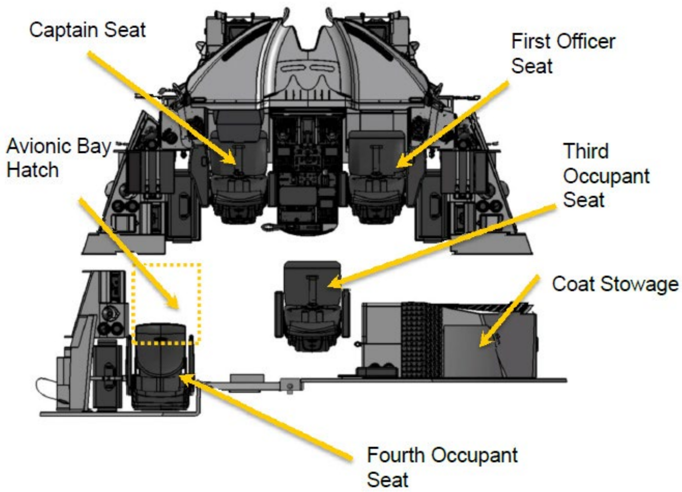
The idea for the cockpit study stems from the findings of the puzzle study, which served as a basis for initial brainstorming. The puzzle study highlighted challenges in precision and usability across interaction modes, informing the cockpit study's design to refine mixed interaction mode in a more applied context. The aim was to explore opportunities identified during the puzzle study by reconsidering and reframing the problems from a fresh perspective, leading to the generation of innovative ideas and solutions. In the context of a cockpit simulator, the concept of one-hand-different-task can be implemented, allowing one hand to grip the controller while the other hand manipulates various components.

To interact with cockpit elements, various solutions have been implemented in cockpit simulators (Oberhauser & Dreyer, 2017). However, based on our current knowledge, the integration of mixed interaction mode to provide user control in flight simulation has not been used before. For effective task support in a cockpit environment, strategic placement of controls and tools at logical locations is crucial (Berg & Vance, 2017). The mixed interaction mode proves to be suitable for such settings. For example, in this scenario, a controller-based mode can be used to hold the sidestick, while the hand gesture mode enables users to manipulate buttons and knobs on the main instrument panels using hand gestures. By combining these input methods, a comprehensive and immersive experience can be achieved during the flight simulation. The implementation of mixed interaction mode is evaluated through a cockpit study, assessing user satisfaction and comfort levels.

The results of the cockpit study can be compared with those of the puzzle study to determine the effectiveness of the mixed interaction mode in the flight simulator. This specific example provides insights into the broader context where real-world problems require different physical movements. Furthermore, the findings can inform the design of future simulators and applications by assessing the suitability of the mixed interaction mode for specific tasks.

The VR cockpit prototype is based on the A350 Airbus flight deck system in A350-900 Flight Deck and Systems Briefing for Pilots. The 3D model was built using Blender software by the author. According to A350-900 Flight Deck and Systems Briefing for Pilots, the A350 cockpit overview in Figure 46 is the general layout of the flight deck, which includes a captain's seat, a first officer's seat, and a third occupant seat (Airbus, 2011).

Figure 46 *A350 Cockpit Overview*



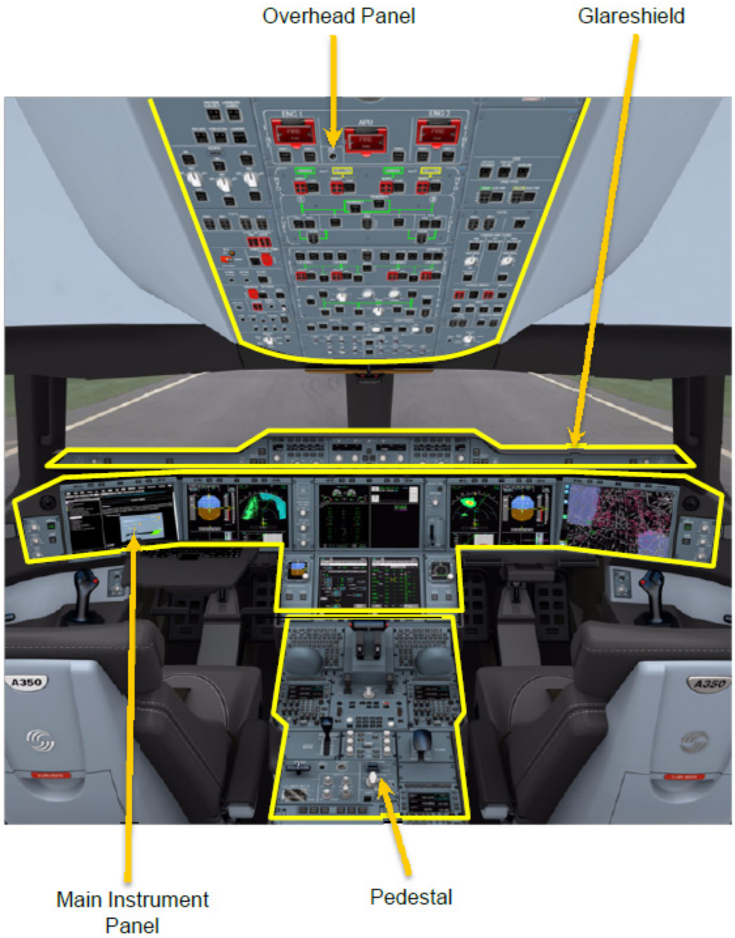
Note. A350 flight deck layout. From "A350-900 Flight Deck and Systems Briefing for Pilots," by Airbus, 2011, p.24.

The cockpit 3D model imported into Unity3D (Figure 47) was created based on the flight deck layout in Figure 42.

Figure 47 *Screenshot of VR Cockpit in Unity3D*

Figure 48 shows cockpit views, including the overhead panel, main instrument panel, glareshield, and pedestal. The captain and first officer have one sidestick, a steering handwheel, and a stowed laptop in the lateral consoles (Airbus, 2011).

Figure 48 *Cockpit Views*



Note. Instrument panels in a cockpit. From "A350-900 Flight Deck and Systems Briefing for Pilots," by Airbus, 2011, p.25.

Figure 49 illustrates the application of textures and materials in Unity3D to the 3D cockpit model. The textures of the main instrument panel, glareshield, and pedestal were derived from Figure 48. This approach ensures a high level of detail and realism in the VR cockpit, enhancing the user's immersive experience. The textures not only contribute to the visual appeal but also play a crucial role in user interaction. Users can interact with these textured elements in a manner similar to a real flight deck, thereby improving the authenticity of the simulation.

Figure 49 *Screenshot of Cockpit View in Unity3D*

Figure 50 presents a participant in the user study employing a mixed interaction mode. The participant used a gloved hand representation for the controller-based mode on the left hand, and a semi-transparent hand for the hand gesture mode. The semi-transparent nature of the hand gesture mode allows users to see through the model, adding another layer of complexity to the interaction.

Figure 50 *Mixed Interaction Mode in VR Cockpit*

Figure 51 illustrates the use of a controller-based mode to manipulate the sidestick on the left side of the cockpit in the mixed interaction mode. This setup allows for a more realistic and intuitive control mechanism, closely mirroring the actual operations in a real-world cockpit. The controller-based mode, represented by a gloved hand in the VR environment, provides tactile feedback and precise control, enhancing the user's engagement and task efficiency.

Figure 52 demonstrates the use of the hand gesture mode for the right hand in the mixed interaction mode. The right hand, represented by a semi-transparent hand in the VR environment, is used to manipulate various cockpit elements such as knobs, switches, and levers. This approach allows for a more natural and intuitive interaction, closely mimicking real-world hand movements.

Figure 51 *Controller-based on the Left Side*

Figure 52 *Hand Gesture on the Right Side*

One of the tasks was designed to evaluate the participant's ability to use the sidestick to balance the flight. The yellow horizon line (Figure 53) was located in front of the flight model, and it was attached to the sidestick using a hinge joint function in Unity3D. This setup enables the participant to simultaneously manipulate both the sidestick and the horizon line, mimicking the real-world task of maintaining flight balance. This task not only evaluates the participant’s ability to use the sidestick effectively but also tests the usability and intuitiveness of the mixed interaction mode in a simulated flight scenario.

Figure 53 *Horizon Line*

5.1.1 Participants

The cockpit study occurred in the same study room at the AUT campus as in the puzzle study. The study aimed to explore the user experience for 3D object manipulation in the context of VR-based cockpit procedure training with mixed interaction, where users were asked to perform interaction tasks with hand gesture mode by using a Leap Motion device on the right hand to control buttons, knobs and levers, and using controller-based mode on the left hand to control the sidestick.

Participant recruitment for the cockpit study began at the AUT showcase event, where the puzzle study was displayed. This allowed for direct recruitment of participants who had interacted with the puzzle study. Further recruitment was done through posters around the AUT campus, which directed potential participants to a Google form for registration.

After registration was completed, a notification was received. An email was then sent, allowing potential participants to understand the project outline and decide on participation. It included the participation information sheet that covers further details of the research. On the participant information sheet, the participants were informed that they could withdraw at any time from the research without being disadvantaged. Discomfort and risks were also mentioned on the participant information sheet, as there might be a possibility that some people might not feel comfortable with VR devices. Participants were also advised to stop immediately when experiencing physical discomfort during the user study. For the health and safety standards, the VR headset was sanitised with sanitising spray after each user study. Subsequently, the participants were asked to fill in the consent form after the user study, and all data collection would remain anonymous.

Eight participants, all with prior VR experience and who had completed the puzzle study either at the AUT showcase event or in a previous puzzle user study at the AUT campus, were individually invited to the cockpit study at the AUT campus. The small number of participants was due to the exploratory nature of this study, focusing on in-depth qualitative data rather than quantitative. Each participant attended a 30-minute session. The study primarily aimed to assess the proficiency of interaction techniques in a new context. Future studies could consider a common baseline for VR technology abilities among participants for more controlled results.

5.1.2 User Study Setup

The user study is designed to explore the user experience of using mixed interaction in the context of cockpit VR training as a specific case of the more general concept. Participants were asked to sit in the middle of the room, and they were given an HTC Vive headset with a Leap Motion mounted on top and one HTC Vive controller before entering the virtual environment. The participants were located inside a virtual cockpit and seated at the captain's seat on the left (Figure 54).

Figure 54 *Captain Seat on the Left in the Virtual Cockpit Environment*

5.1.3 User Tasks

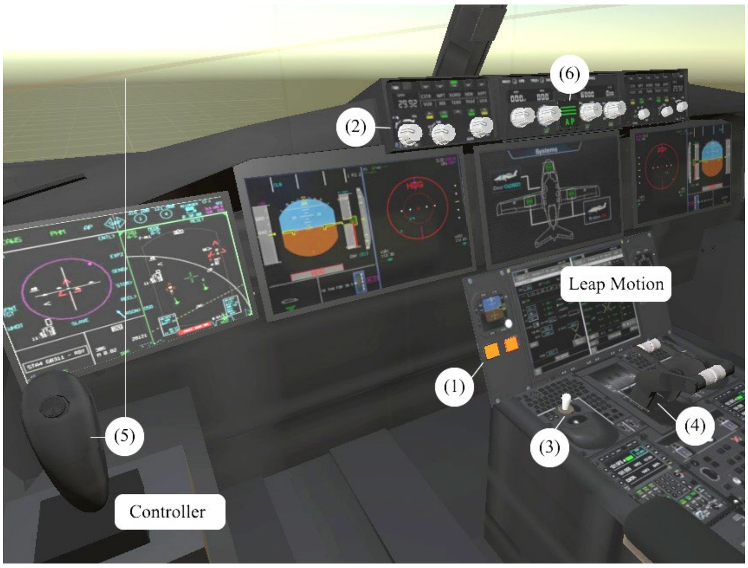
The user study was designed to assess participants' experience in a cockpit scenario, building upon the findings from the previous puzzle study. While the puzzle study focused on more complex and physically demanding manipulation tasks, the cockpit study aimed to explore how participants interact with more intuitive, real-world controls, providing insight into the usability of the mixed interaction mode in a more applied context. The six tasks selected were intentionally simple to focus on basic but crucial interactions commonly found in cockpit operations.

These tasks were designed to investigate how users engage with both controller-based and hand gesture modes in a virtual environment simulating cockpit tasks. Unlike the puzzle study, which emphasised intricate manipulation, the cockpit tasks focused on intuitive control, basic task execution, and understanding how different interaction modes perform in a scenario that mimics real-world environments. The simplicity of these tasks allowed participants to focus on mastering the mixed interaction mode rather than being overwhelmed by complex problem-solving.

The scenario also focused on the participants' ability to use the HTC Vive controller to balance the flight with their left hand (Figure 55). The tasks were designed to mimic real-world cockpit operations, including manipulating virtual knobs, pressing buttons, pulling levers, and balancing the flight. The tasks participants were asked to complete included:

1. Turn on the orange integration button (located at the bottom right of the front panel)
2. Rotate one of the knobs to the right (on the front panel)
3. Flicking a white switch (on the pedestal panel to the right)
4. Pushing the lever (on the pedestal panel)
5. Using the sidestick to balance the position of the plane (on the left-hand side)
6. Pressing the green autopilot button (in the middle of the front panel)

Figure 55 *Controller-based and Hand Gesture modes in a Cockpit*



Note. Step 1-6 indicate the six tasks in the study.

5.1.4 Interview

The aim of conducting interviews as part of the cockpit study is to allow for deeper qualitative data to be collected around a new user task designed to drill down into specific scenarios from the initial puzzle study. Qualitative inquiry allows researchers to listen to their participants' voices and have conversations with them. This type of inquiry empowers the participants by allowing them to share their stories (Lewis, 2015). The data collection protocols are simplified from the original user tasks in that quantitative data is no longer collected, and the survey instruments used to follow the research tasks have been condensed into a small number of interview questions (Appendix 13).

The interview analysis followed the six phases of thematic analysis developed by Braun and Clarke (2006). Phase 1 begins with familiarising oneself with the data through transcribing and repeated reading. Codes were identified when data was studied thoroughly in phase 2. The researcher then searches for potential themes after reviewing codes in phase 3. In phase 4, an initial map of themes was produced, and data were analysed to check if they supported the themes. In phase 5, the researcher revisits the connections between the themes and the thematic map to generate a clear definition of themes. Finally, the researchers select the apparent data to describe the themes and analyses the data in relation to the research question (Braun & Clarke, 2006).

5.1.5 Summary

The cockpit study was conducted to explore user experiences in a VR-based cockpit scenario, specifically focusing on the use of mixed interaction mode in a simulated scenario. The study involved 3D modelling, material applications, task design, and VR technical solutions. It aimed to identify users' natural reactions and interactions with various object manipulation tasks in a virtual environment.

The study aimed to assess the effectiveness of the mixed interaction mode in different task contexts and to gain insights into how this mode influenced user experiences. It investigates the practical applications and potential benefits of using mixed interaction in more complex environments.

Following the user study, in-depth interviews were conducted, allowing participants to share their experiences and provide suggestions for further improvements. The findings from the interviews will be reported in the next section and are expected to expand the existing knowledge of VR object manipulation design guidelines by summarising the suitability of the interaction tasks in a virtual environment.

5.2 Results

The section presents the interview data findings, and a data analysis procedure is introduced. This single qualitative study aims to identify the similarities within the thematic analysis approach to highlight and apply codes and create initial themes based on the comments from the participants in the cockpit study, followed by a finalised thematic map with the main themes. It also presents each theme with examples of participants' answers and explains how the themes were formed.

The study results reveal specific insights addressing the user experience, challenges, feedback for improvements and the potentials of mixed interaction mode development. This study is explanatory and sequential. Therefore, the qualitative analysis is considered best suited for this study. This research emphasises outcomes and has produced a set of guidelines and considerations to be taken into account by designers when developing virtual environments that incorporate various forms of interaction. These guidelines, which are detailed in Section 6.4, aim to inform future practices and serve as a valuable reference, particularly for identifying the types of tasks best suited to a mixed interaction mode.

5.2.1 Data Analysis Procedures

The interview in the cockpit study was intended to gather the experiences, opinions and understandings from a small number of people with previous VR experience. Eight interviews were conducted in a private room at Auckland University of Technology. Each one-on-one interview was audio-recorded and lasted around 20 minutes. Google's speech-to-text function was used to validate the accuracy of the transcripts, ensuring that every spoken word was captured as accurately as possible. Google does not retain the data inputted into their speech-to-text function, ensuring the confidentiality of the participants' responses. According to Fusch and Ness (2015), it is vital to consider the data sample selection and the design for reaching data saturation. Walker (2012) suggests data saturation is achieved when enough information is collected in a study. Questions such as "Why?" and "Can you elaborate?" were asked to collect more information from the participants to understand their perspectives fully. After conducting eight interviews, the interview responses met data saturation, where no new insights were provided from the participants to the interview questions. Since the questions were very focused, relatively low numbers of participants were sufficient to achieve data saturation.

The purpose of conducting a thematic analysis is to generate themes and address the research questions. According to Braun and Clarke (2006), thematic analysis is used to analyse the interview data, and codes are developed from the transcripts and analysed into initial themes, sub-themes and main themes. The raw data were used to identify meanings and organised into patterns, and the results of themes will be written in relation to the aim of the study context (Sundler et al., 2019). The analysis can reveal the participants' opinions, attitudes and beliefs and provide insights into the data to help answer the research question.

5.2.2 Interview

This section presents the data analysis results from eight interviews following the thematic analysis process. In the code generation, the transcribed data were selected from each interview, followed by defining initial themes to narrow the codes into relevant themes. The themes are primarily aligned with the research question, including experience with interaction tasks, the mental and physical workload in mixed interaction mode, user satisfaction, usability, innovation experience, and potential for mixed interaction mode. Table 11 includes the interview questions corresponding to the research question.

Table 11 *Main Discussions Aligned to Interview Questions*

Main discussion during the interviews	**Interview Questions**
Interaction task experience	Can you describe how you found the interaction task?
Mental and physical workload	How demanding, both physically and mentally, did you find the task?
User satisfaction	How successful do you think you were in conducting the task?
Usability of mixed interaction mode	How did the mixed interaction mode contribute to your success?
Innovation experience	What will be the difference if you were given a set of controllers or using only Leap Motion?
Potentials in mixed interaction mode	What sort of use cases can you see as benefiting from this type of mixed interaction mode?

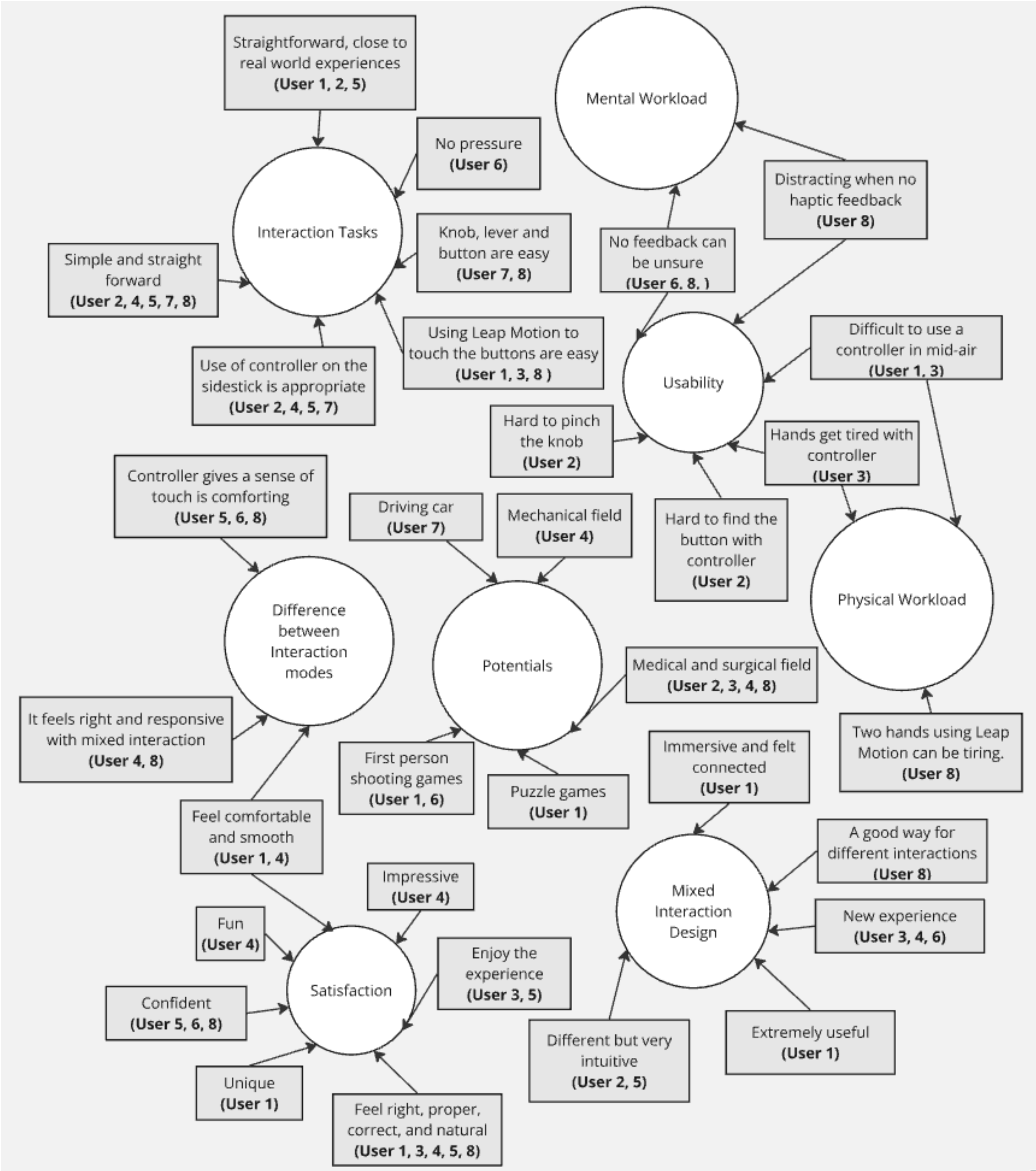
Transcription involves observing data through repeated listening (Bailey, 2008). The transcriber listens to the audio, interprets the content, and then types up a written version. It includes capturing every spoken word as accurately as possible. The interview data analysis process follows the six steps of thematic analysis (Table 12) developed by Braun and Clarke (2006).

Table 12 *Phases of Thematic Analysis*

Phase 1	Familiarising yourself with your data
Phase 2	Generating initial codes
Phase 3	Searching for themes
Phase 4	Reviewing themes
Phase 5	Defining and naming themes
Phase 6	Producing the report

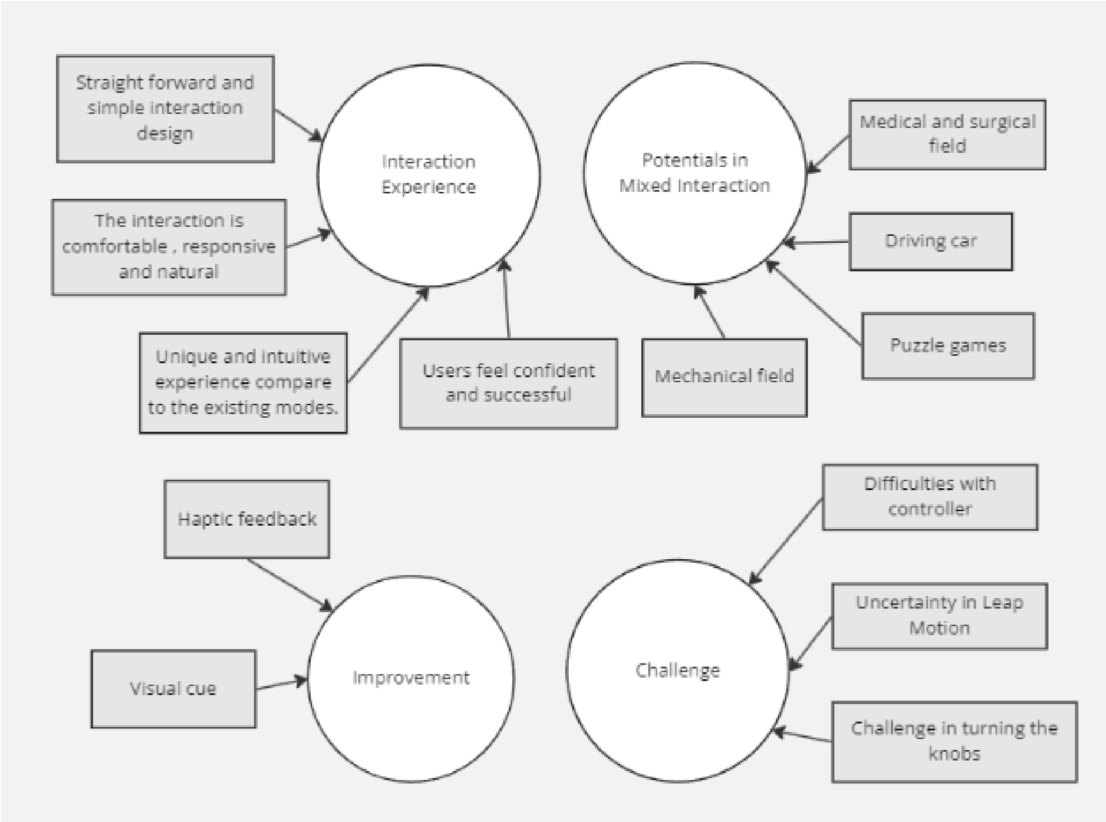
The thematic analysis combines the frequency of codes, and the codes describe the majority of the data (Joffe, 2011, p.226). Following phase 1 in the thematic analysis developed by Braun and Clarke (2006), some phrases were highlighted in different colours after reading through the data and becoming familiar with it (Appendix 14). In phase 2, the highlighted phrases were transformed into different codes, and each code on the right side describing the feeling or expression in that part of the comment. In phase 3, while adding new codes in the process, the aim was to search for themes by looking for noticeable keywords. In phase 4, the keywords were grouped into clusters based on their similarities. These clusters are depicted in the initial thematic map (Figure 56), which was created after a thorough review of the themes. Each cluster is annotated with the number of participants who contributed to it. These numbers are indicated in parentheses, providing a clear differentiation between clusters that represent individual experiences and those that reflect common user experiences. In phase 5, the final themes result from the process of defining and renaming the main themes and sub-themes in Figure 57. Finally, the report in phase 6 is discussed in the following sections.

Figure 56 *Initial Thematic Map*



The process of theme searching involves how similar codes can be combined and sorted to form a theme (Nowell et al., 2017). After constantly revisiting the data, four main themes with sub-themes developed from the analysis are "Interaction experience", "Improvement", "Challenge", and "Potentials in mixed interaction" (Figure 57). A detailed discussion of each theme follows the table.

Figure 57 *Final Thematic Map*



In the following sections, the themes and example quotes are presented.

5.2.2.1 Theme 1: Interaction Experience

Participants were asked about their perception of the interaction task given in the user study. Participants defined the term interaction task experience differently. The interaction experience therefore focused on: 1) interaction design, 2) interaction experience, 3) the experience compared to the existing modes, and 4) user satisfaction.

Table 13 summarises the answers from 8 participants (Participant 1 – Participant 8), from codes and initial themes to main themes and sub-themes. For the initial themes, the most frequently used words are “easy, straightforward and simple”, “natural and responsive”, “confident and successful”, “unique and intuitive”, and “fun and enjoyable”. Therefore, the themes were considered initial themes reflecting the main theme, “Interaction experience”.

Table 13 *Participants' Inputs on Interaction Tasks Experience*

Code	Initial themes	Main theme	Sub-themes
Straightforward and simple. Knob, lever and button are easy.	Good interaction design	Interaction experience	Straightforward and simple interaction design
It feels connected, comfortable, responsive, and natural	The interaction is comfortable, responsive, and natural		Feelings and expressions from the interaction experience
No pressure and confident	Users feel confident and successful		Users feel confident and successful
Mixed interaction is unique and intuitive	New and enjoyable experience		Experience compared to the existing modes.
Fun and enjoyable			

The sub-themes are described below with examples of comments from the participants:

Straightforward and Simple Interaction Design

The analysis concentrated on the critical statements made by the participants who focused on interaction task design as below:

- Participant 1- "For the pushing the controls backwards and forwards and flicking the switches that was easy…The directions are very straightforward so it was good."
- Participant 2 - "I found them fairly simple and straightforward forward most of the stuff like the knobs and flicking the switch was I just kind of know how to do based on real world experiences…"
- Participant 3 - "The interactions, they work surprisingly well to be honest and I especially for it just tracking my hand and being able to interact with the environment that so much like it's a strange experience at first, but it almost is like second nature in a way it feels and like I'm actually there it's super cool everything works really well."
- Participant 4 - "They were very simple to do…the instructions were clear, and everything was quick and easy to do."
- Participant 5 - "The tests were very simple and straightforward and I enjoy it."
- Participant 8 - "The leap interaction is very very very very good I could see and map the movement of my hand with the movement of the representation in the game, so it was easy to use, it was not hard to try to do things and try to find how to press things or to move things."

Feelings and Expressions from the Interaction Experience

Some participants expressed their feeling from the interaction experience with different expression terms:

- Participant 1 - “It was very unique experience to have … it's already immersive sitting in the cockpit and actually touching and moving the controls. The right hand, the ghost hand and there was very connected.”
- Participant 2 - “It was quite intuitive as well, being able to use fingers to press buttons.”
- Participant 3 - “It's quite leisurely compared to a lot of like other VR activities.”
- Participant 4 - “It was quite fun actually being able to interact with like being able to use my entire hand also like having the other hand ready on the joystick to actually move it around…everything else felt really smooth and it was really impressive to see it actually just know my hand was there but immediately work with it.”
- Participant 5 - “They are totally different but feels very intuitive to a person who uses a computer all the time.”
- Participant 8 - “The interaction in general, it was easy it was visually appealing… It's easy because it was responsive that there was no delay in the movements the connection was good… you try to naturally do that and it responded to it so it is easy.”

Users Feel Confident and Successful

Most of the participants commented on their mental workload, confidence and satisfaction after the task completion:

- Participant 1 - “Not demanding at all. It's very smooth and very easy.”
- Participant 2 - “I think that goes pretty successful once I got the hang of it.”
- Participant 3 - “I felt like I was successful thinking back I’d say like 80%.”
- Participant 4 - “Didn't feel it stressful…everything felt snapping smooth, and it was really easy quickly do everything once you told me which part was.”
- Participant 5 - “I think I did very well.”
- Participant 6 - “I found it yeah it's almost easy… I feel no pressure.” “I ticked all the boxes right and very confident.”
- Participant 7 - “I didn't need to use any mental capacity to do any of the tasks…Pretty successful…like pressing levers and turn knobs are pretty easy.”
- Participant 8 - “I suppose it was quite successful.”

Experience Compared to the Existing Modes

Furthermore, some participants compared the existing modes to express their interaction experiences as below:

- Participant 1 - "I think that it was extremely useful… I feel comfortable with the mixed controller."
- Participant 2 - "I think it was contributed because being able to have controller in one hand and able to have the other hand free, was I think much easier than using two controllers for me personally like having like rather trying to focus on two physical objects in your hand once having one hand like freely move, the other hand being able to hold controller and do stuff as well."
- Participant 3 - "It definitely just added an entirely new way of how it felt. I think it was super I think it definitely did as it was super interesting."
- Participant 4 - "It was definitely quick to tell that I could know the ease of having that free hand to do whatever I needed with my fingers and having the other hand just ready to move probably. It felt right it felt proper it felt correct like yeah like being able to freely do anything with my other hand while the other while my left hand was meant to be on the joystick ready to move it around and felt really naturally basically… it just definitely feels a lot more natural just being able to point and press my finger against than smashing the entire controller into it."
- Participant 6 - "If I'm exposed enough to Leap Motion, the whole thing i would do ok with it. So, I like the mixed."
- Participant 8 - "With only controllers maybe I would feel a little more in control but I feel more comfortable with the mixed interaction."

Regarding the interaction mode, participants found the hand gesture and the controller-based modes easy and straightforward to use. The hand gesture mode, in particular, was praised for its naturalness and responsiveness, with users able to perform tasks such as touching buttons with ease. Moreover, Participant 4 raised an issue with collisions when using two controllers, indicating a potential area for improvement in the technology.

On the interaction side, participants found the tasks to be simple and straightforward, with most feeling confident and successful in their performance. The tasks, which included core actions such as turning knobs, pulling levers, and pushing buttons, were designed to mimic real-world interactions, contributing to the ease of use reported by the participants.

Participants' emotional responses to the tasks were generally positive, with words such as "unique", "definitely", "very intuitive", "natural", and "very, very, very, very good" frequently used to describe their experiences. The naturalness of the tasks was particularly highlighted, with Participant 1 enjoying the ability to move their hands naturally and Participant 4 finding it natural to point and press objects freely.

When comparing the mixed interaction mode to existing modes, participants found it to be a unique and intuitive experience. Participant 8, for example, enjoyed the new interaction mode where they could naturally pinch and grab objects in the virtual environment. Participant 5 described the experience as different and intuitive, similar to using a keyboard and a mouse.

5.2.2.2 Theme 2: Challenge

The participants were asked about the workload of the interaction task that was given in the user study. Participants described their mental and physical workload from different perspectives. The challenges focused on: 1) difficulties with the controller-based mode, 2) uncertainty in hand gesture mode, and 3) the challenge of turning the knobs. Table 14 summarises the answers from 8 participants (Participant 1 – Participant 8), from codes and initial themes to main themes and sub-themes. For the initial themes, the most frequently used words are "no feedback can be unsure", "Hands get tired with the controller", "Difficult to use a controller in mid-air", "Hard to pinch the knob", and "Hard to find the button with controller". Therefore, these themes were considered initial themes reflecting the main theme, "Challenge".

Table 14 *Participants' Inputs on Challenge*

Code	Initial themes	Main theme	Sub-themes
No feedback can be unsure	No feedback can be unsure	Challenge	Difficulties with the controller
Hands get tired with controller	Hard to find the button and hands get tired with controller		Uncertainty in Leap Motion
Difficult to use a controller in mid-air	Difficult to use a controller in mid-air		The challenge of turning the knobs
Hard to pinch the knob	Hard to pinch the knob		
Hard to find the button with controller			

The sub-themes are described below with examples of comments from the participants:

Difficulties with the Controller

Participants expressed challenges with the controller. For the code generation, the analysis concentrated on the key statements made by the participants who considered the challenge as:

- Participant 1 - “Holding the controller like you have the hand floating in mid-air and is a very disconnected feeling ..., the knob was difficult to get the technique right to adjust.”
- Participant 2 - “With controllers it's more so like the struggle is also finding where the buttons are to control and all that as well.
- Participant 3 - “Pushing buttons it's probably the most difficult was that the stick is my hand was a bit shaky because it's in the mid air…The Vive controller it sometimes I've played with those in the past, so it gets like real finicky trying to pick things up or my hand gets tired whereas this didn't feel like any fatigue was on my hand at all, so it was it is a lot easier to actually use my real hand”.
- Participant 4 - “There was some difficulties like previously mentioned about the turning the dial.”

Uncertainty in Leap Motion

Participants expressed challenges with the hand gesture mode. For the code generation, the analysis concentrated on the key statements made by the participants who considered the challenge as:

- Participant 2 - "It took me let's say like a minute to get used to the leap motion cause it was quite weird using actual fingers cause I'm so used to buttons like physical buttons on the controller."
- Participant 5 - “For the leap motion you don't know if it's triggered or not ”.
- Participant 6 - "There's no feedback with leap motion so you are always blindly pushed into something”.
- Participant 7 - "With the leap motion when you need like grabbing something it feels like everything is just weight nothing…. It's like if I had no touch or anything it's like trying to pretend that you're turning the knob or something."
- Participant 8 - “It can be a little stressing or tiring, so the leap motion would need some more type of feedback or guideline of feedback or something to compliment that lack of physicality… You don't have the haptic feedback; it could be a little distracting. "

The Challenge of Turning the Knobs

Participants mentioned that it is difficult to turn the knobs as below:

- Participant 1 - "the knob was difficult to get the technique right to adjust."
- Participant 2 - "I found with the knobs that are to pinch quite hard."
- Participant 4 - "There was some difficulties like previously mentioned about the turning the dial."
- Participant 5 - "I don't know if I'm holding a knob yet, unless is like a very significant visual indicator that it's been triggered".

From the perspective of interaction modes, some participants reported feeling fatigued when using the controller-based and hand gesture modes. Participant 1 experienced a sense of disconnection when their hand was floating in mid-air with the controller. Similarly, Participant 3 reported a sensation of hand shaking when their hand was suspended in mid-air, leading to fatigue from picking up objects.

In terms of interaction tasks, Participant 5 expressed uncertainty when attempting to hold a knob due to the absence of a visual indicator from the hand gesture mode. This sentiment was echoed by Participants 6, 7, and 8, who described feelings of uncertainty, stress, and fatigue with the hand gesture mode, particularly when there was no physical weight or visual and haptic feedback during task interactions.

5.2.2.3 Theme 3: Improvement

The participants were asked about the usability and possible improvements of the interaction task that was given in the user study. Participants defined the usability differently. The improvements therefore focused on: 1) haptic feedback and 2) visual cues. Table 15 summarises the answers from 8 participants (Participant 1 – Participant 8), from codes and initial themes to main themes and sub-themes. For the initial themes, the most frequently used words are "No feedback", "Distracting", and "Visual cues". Therefore, the initial themes reflected the main theme of "Improvement".

Table 15 *Participants' Inputs on Improvement*

Code	Initial themes	Main theme	Sub-themes
Distracting when no haptic feedback	Distracting when no haptic feedback	Improvement	Haptic feedback
No feedback can be unsure	No feedback can be unsure		Visual cue
Need a little bit more visual flair	Visual cue needed		
Reply on visuals when no haptic feedback			
Require a very significant visual indicator			

The sub-themes are described below with examples of comments from the participants:

Haptic Feedback

Participants suggested some potential improvements for the interaction experience. For the code generation, the analysis concentrated on the key statements made by the participants who suggested improvement in the following:

- Participant 3 - "Some sort of haptic feedback with vibrations which may go like a bit further and selling the experience."
- Participant 6 - "I just had to think about the how much force or how far do I extend my arm out and all that stuff because obviously there's a lag time between the lidar feedback and the hand haptic feedback."
- Participant 8 - "Because there is no like haptic feedback for the hands so you only have to rely on visuals…Very very very worth or try to find some way of having your hand free but still giving feedback that would be quite a challenge."

Visual Cue

Participants suggested some potential improvements in visual enhancement. For the code generation, the analysis concentrated on the key statements made by the participants who suggested improvement in the following:

- Participant 5 - "Unless is like a very significant visual indicator that it's been triggered."
- Participant 6 - "Like you're always just trying to visually depend on like visual cues."
- Participant 8 - "The response, maybe it needs a little bit of more visual flair, it suppose like visual indication of when you're interacting with your right hand…with the leap, it needs more hover effect, with something that indicates that you are actually interacting with… sometimes

just seeing the thing moving or especially the buttons like are you pressing it or not, so a more visual distinct visual representation would be better… if you pair that with visual cue, you can feel it and you can feel in control”

In general, participants provided valuable feedback for potential improvements in the user study. From a technology perspective, they suggested the incorporation of haptic feedback, such as vibration, to provide users with real-time information on the current state of the task or to alert users to potential obstacles. For instance, Participant 3 suggested the use of haptic feedback with vibrations to enhance the experience.

From an interaction standpoint, participants highlighted the need for visual cues, such as the hover effect from hand gesture mode, to help users keep track of their progress and provide feedback on their performance. Participant 8, for example, suggested more visual cues from hand gesture mode, such as a hover effect, to indicate interaction.

5.2.2.4 Theme 4: Potentials in Mixed Interaction

Participants were asked to provide suggestions of potential applications they considered applicable for adapting mixed interaction mode. The responses therefore focused on: 1) the medical and surgical field, 2) VR games, and 3) the mechanical field. Table 16 summarises the answers from 8 participants (Participant 1 – Participant 8), from codes and initial themes to main themes and sub-themes. Moreover, these initial themes reflected the main theme, “Potentials in mixed interaction”.

Table 16 *Participants’ Inputs on Potentials in Mixed Interaction*

Code	Initial themes	Main theme	Sub-themes
Medical and surgical	Medical and surgical	Potentials in mixed interaction	Medical and surgical field
Driving car	Driving car		VR games
Mechanical	Mechanical		Training
Mini games	Mini games		
Puzzle games			
First person shooting games			

The sub-themes are described below with examples of comments from the participants:

The Medical and Surgical Field

Participants suggested some potentials in the medical and surgical field using mixed interaction mode. For the code generation, the analysis concentrated on the key statements made by the participants who suggested improvements in the following:

- Participant 2 - “Surgery, if you have the left hand for like surgical scissors like physical objects that you hold right in the right hand for like moving stuff around the patient and like picking objects up… there is already surgery kind of VR games out there both controllers and a lot of doing surgeries finicky stuff of fingers right it also stuff of objects so it's kinda good to being able to do both, having mixed of interactions.”
- Participant 4 - “A surgery SIM you've got that all in one hand and you've got like more precision stuff with your left hand, stuff like that like just being able to do more precise like a little pinch and pull rather than grabbing the entire thing in just being a way.”
- Participant 8 - “I quite like your finger or pinching or a more little precision like fitness movement like surgery centre for example that would be interesting because you can do that with more technology like the purpose scenarios like fitness is necessities is what you want more precise interaction.”

Participants highlighted the potential for precise interactions in surgical settings using mixed interaction mode. They suggested using one hand for tools and the other for delicate tasks. The distinction between hand and tool simulation is crucial. The controller-based mode may be effective for some tasks, but it may not offer the same precision as direct hand simulation. It could be used for ray casting but may not provide the same level of immersion or intuitive control as direct hand interaction. Therefore, further research is needed to optimise these interaction techniques for medical applications.

VR Games

Participants suggested some potential applications in the VR game using mixed interaction mode. For the code generation, the analysis concentrated on the key statements made by the participants who suggested improvements in the following:

- Participant 1 - “First person shooters if you bring your second controller up and you'll have to hold the grip and pull the slide back but you commonly smash the two controllers together because that too close… and I think it's huge that will be hugely beneficial for certain types of games probably puzzle games too, where instead of having to have the controllers you can slide things around and connect wisely."

- Participant 3 - "You know the game Boneworks? yeah so that was I played that on my vive and that's one of those games that had you used the bottom grip to hold onto things so I would have to take like kind of intermittent breaks to rest my hands …I notice that when you try to put something close together the controllers will hit each other like they crash into each other."
- Participant 4 - "A magic fantasy base like you have a sword in one hand and you have like your right hand doing spells like doing little finger motions to do the magic oh like doing your finger movements."
- Participant 5 - "Almost mini game kind of aspects I feel benefit the most, I feel like many detail thing, for example like a flashlight with one hand for the controller actually you feel you're grabbing it, turn it on with finger grab and then you can do something intricate with your other hand …that could be mixed I feel."
- Participant 6 - "Shooting simulator games….just like having the controller too ah actually yeah the mixed one would work, say if you want to reload a gun in a fps shooter game, that'll be a really cool feature to be able to if you say if you're holding like a bold actions sniper rifle, that you can display manually like grasp on the bolt and then like eject the bullet I mean like in the shooting game but yet so the rifle you manually load the thing in with the with the leap motion and then you still have the controller then like holding the gun."

Training

Participants suggested potential applications in VR training using mixed interaction mode. For the code generation, the analysis concentrated on the key statements made by the participants who suggested improvements in:

- Participant 1 - "PC building simulator pro where you pull components out if you had the ability to actually grab it with your hand and yank it out of the PC and do those sorts of procedures you could really train somebody to build a computer without having the fear that they would blow up your room."
- Participant 4 - "Mechanical stuff like teaching people how to use certain things even like cooking like having like the whole like from one hand having like the left doing the cutting would be really cool to have like that sort of stuff like just day to day SIM just job SIM."
- Participant 7 - "Driving cars like if you were to drive a car you could use a controller to do the stick and other hand just turning the wheel."

- Participant 8 - “Training of heavy machinery or complicated machinery in general in which very interesting because you don't need to the big machine… with what you are supposed to learn and you can train perfectly well which is completely transferable your abilities from the virtual world to the real world.”

The participants’ feedback suggested several potential applications for mixed interaction mode, particularly in VR games, training, and surgical simulations.

Participants saw potential for mixed interaction mode in VR games, particularly shooting games. They noted that using hand gesture mode to simulate actions like loading a rifle could reduce common issues such as collisions between two controllers at close distances. This feedback highlights the potential of mixed interaction mode to enhance the gaming experience by providing more natural and intuitive control methods.

Participants suggested potential applications in training scenarios that require both hands to manipulate objects differently, such as cooking and driving simulators. This feedback underscores the potential of mixed interaction mode to provide a more realistic and effective training experience.

Participants also suggested potential applications in the medical and surgical field. They highlighted the advantage of performing precise actions, such as using one hand for surgical scissors and the other for a different tool or action. This feedback suggests that mixed interaction mode could be beneficial in scenarios that require precision, such as surgery.

5.3 Summary

This chapter presented the findings from the cockpit study, which aimed to explore the practical applicability and user experience of the mixed interaction mode in a more complex context. Participants in this study showed interest in the VR cockpit simulator and the mixed interaction mode. By engaging in the designed tasks, participants were given helpful information about the practice of designing VR interaction tasks and were able to reflect on their interests and preferences.

Participants reported feeling more comfortable and in control when using the mixed interaction mode, highlighting the importance of intuitive and user-friendly VR systems. This feedback offers important implications for improving the design of VR applications and informs future developments in the field.

When comparing the cockpit study to the earlier puzzle study, key differences emerged in the design and feedback regarding the interaction mode. For instance, while the puzzle study suggested that task completion times with mixed interaction mode were comparable to or slightly better than traditional controller-based mode, the study design and potential learning effects may have influenced this observation. Therefore, while the mixed interaction mode appeared promising in terms of task completion times, further investigation would be needed to confirm these findings in a more controlled setting. The cockpit study, however, provided context-specific data, as it involved tasks designed specifically for mixed interaction mode. This revealed where the mode could be more intuitive or effective. This comparison highlighted that the mixed interaction mode may work best in scenarios tailored to its features, though it presents usability challenges when applied to general tasks, as noted in the puzzle study.

Several themes emerged from the cockpit study interviews, such as the need for user adaptability and flexibility in control methods. Participants appreciated the mixed interaction mode, yet some felt overwhelmed by the variety of available options, particularly in complex tasks. This feedback paralleled insights from the puzzle study, where participants also noted control confusion, underscoring the need for clearer guidance and streamlined interactions in both studies.

These findings underscore the value of sequential data triangulation across the two studies. While the puzzle study provided preliminary insights into the potential of the mixed interaction mode, the cockpit study's context-specific task design allowed for a more detailed exploration of its application in a real-world scenario. Together, these studies provide a more comprehensive understanding of the mixed interaction mode's capabilities and areas for improvement.

Furthermore, the feedback from the participants provided valuable insights into how the interaction mode can be improved to better meet user needs and preferences, including more options for customising the experience and more guidance for users who are unfamiliar with the technology. The findings also suggest that the mixed interaction mode could be used in a variety of contexts, depending on the user's needs and preferences. The next chapter will provide a broader summary of the research, including recommendations and directions for future work.

Chapter 6: Discussion

This chapter provides a discussion of the results of the two studies conducted in this paper: the puzzle study and the cockpit study. The results from each study are placed within the context of the relevant existing literature. To facilitate a clear and coherent discussion, the puzzle study results will be discussed in Section 6.1 first, followed by the discussion of the cockpit study in Section 6.2. In Section 6.3, answers to the research question are presented, and design guidelines are suggested in Section 6.4 for future development.

6.1 Puzzle Study

The objective of the puzzle study is to understand the strengths and weaknesses of the controller-based, hand gesture and mixed interaction modes by collecting task completion data from the user study. The results discussed in this chapter help to understand user performance and user experience in VR interaction developments. Overall, the findings from this study aim to understand the user experience of the mixed interaction mode compared to using a controller-based and hand gesture modes.

6.1.1 Participant Use of Hand(s) Measures

The findings of the puzzle study, which indicate that using two hands to complete the physical and VR puzzles is the preferred method for task completion time, directly address the central research focus of this study, which is to determine how users' task performance impacts the effectiveness of mixed interaction mode in VR.

This study was designed to evaluate user experiences using mixed interaction mode in VR and to identify the potential applications of such approaches. The results suggest that two-handed interactions could lead to a more intuitive and engaging user experience, as evidenced by Drogemuller et al. (2020) who found that two-handed flying was faster and more preferred by the participants for navigation. This aligns with the aim of improving user experience in VR applications through the exploration of mixed interaction mode.

Moreover, the use of hand(s) measures in this study also indicates that the percentage of participants using both hands during the mixed interaction mode is greater than the percentages for the controller-based and hand gesture modes. This result is consistent with the findings of Olmedo et al. (2015), who found that the main issue with VR and HCI integration may be related to the efficiency of the integration.

In HCI, the relationships between users and computers are shaped through interfaces, allowing users to express themselves effectively through different media or tools (Rogers, 2022). The study results highlight the potential of mixed interaction mode to improve user experience in VR applications. According to Frank and Kapila (2017), a mixed reality interface seeks to unify the physical and digital realities by creating seamless transitions between them and allowing the co-existence and interaction of real and virtual objects and environments in real-time.

The results of the studies discussed herein support the multimodality notion proposed by Yang et al. (2019), which suggests that incorporating multiple sensing methods enables users to interact more naturally and efficiently. According to the results, users achieved better performance outcomes when using both hands simultaneously for their tasks than when using only one hand. This is further supported by Mundt and Mathew (2020) who found that the two-handed radial menu is more efficient in terms of usability, user experience, presence, error rate, and selection time.

The results of the study indicate that participants who utilised both hands in the VR environment experienced improved control and precision during object manipulation tasks. This enhancement allows users to explore all possible combinations of objects or movements more effectively. As noted by Li et al. (2018), the flexibility in interaction modes significantly contributes to users' ability to manipulate objects in virtual spaces more intuitively. Furthermore, employing both hands can enhance the user’s sense of engagement with the puzzle. The findings align with the work of Hasan and Yu (2017), who highlighted that bimanual interaction in VR not only improves task performance but also increases user immersion and presence within the virtual environment. By allowing users to physically and mentally interact with the objects or movements, two-handed input fosters a more compelling and engaging experience. Moreover, research conducted by Drogemuller et al. (2020) indicates that two-handed interactions allow users to achieve a more immersive experience, which reinforces the importance of physical engagement when solving complex tasks.

6.1.2 Task Completion Time

The puzzle study indicates that the mixed interaction mode shows the best median in task completion time among the three interaction modes for Puzzle 1, suggesting that mixed interaction mode is more efficient for completing Puzzle 1 quickly than the controller-based and hand gesture modes. However, the median of the controller-based shows better results in Puzzle 2. The findings are consistent with the results of Huang et al. (2021), as their quantitative evaluation demonstrated that the mixed interaction mode of interaction consistently led to faster task completion times compared to hand gesture mode, and in certain cases, even outperformed the use of controller-based mode alone. However, it is important to note that due to the study design, including potential learning effects, these findings may not necessarily reflect true performance differences, and further investigation is needed to confirm the efficiency of the mixed interaction mode in a more controlled setting.

In Puzzles 1 and 3, the interquartile range of the controller is wider than the other modes, and the task performance is not as stable as the other modes during the user study. The controller-based mode likely requires the user to interact physically with the system, meaning that the user's performance may vary depending on the individual's physical capabilities and experience level. The controller-based mode involves more complex physical movements than the other modes, indicating a larger interquartile range. This is supported by studies such as those conducted by Lou et al. (2021), which found a hand-adaptive UI to be more efficient and less physically demanding.

Furthermore, from the talk-aloud verbal summary, Participant 30 felt that the controller-based mode was more tiresome than hand gesture mode, which aligns with findings from other participants who also reported some discomfort with the mixed interaction mode. This is consistent with the work of Rantamaa et al. (2022), who suggested mechanical redesigns to improve current VR controllers by addressing issues like fatigue, discomfort, and bulkiness. Additionally, Lou et al. (2022) found that using a controller for extended periods can lead to fatigue and discomfort, as well as strain on the user’s hands and wrists over time

Moreover, Kangas et al. (2022) and Nanjappan et al. (2018) found that hand gesture manipulation of simple objects is advantageous for one-hand manipulations. In contrast, controller-based manipulation proved to be more efficient for two-handed manipulations. The present research results may have been influenced by the extent to which users relied on one or two hands during the experiment. Therefore, it is essential to consider the balance between control type and hand preference when performing similar studies in the future.

These observations illustrate a direct correlation between the physical demands of the controller and task performance. The combination of participant feedback and task performance metrics highlights the importance of incorporating ergonomic considerations into VR controller design, ultimately enhancing user experience across various interaction modes.

6.1.3 Questionnaire Discussion

6.1.3.1 Questionnaire Findings

Users were asked to complete the questionnaires to rate their experience and perception of the UI's usability as part of the evaluation process. The results provide valuable feedback to help improve the quality of the prototype. For questions 1 – 11, the controller-based mode scored higher overall than both hand gesture and mixed interaction modes. This contrasts with the study by Hsiao and Chen (2016), which found that a gesture-interactive game-based learning approach was more effective than a traditional activity game-based learning approach. However, the present study has indicated that participants felt more confident when using the controller-based mode, likely due to their prior experience with such devices. The traditional layout of the controller allows for faster adaptation and improved usability, although it remains to be seen if such increased user comfort leads to improved performance. Additionally, in order for users to experience an improved user experience, the Leap Motion needs to update the current software to a newer version and further improve its pinch movement capabilities.

The study results indicate that a controller-based mode functions efficiently, offering ease of use and effective object selection. Moreover, user satisfaction and usability measurements had higher median scores, suggesting that the participants perceived the controller-based mode favourably compared to the hand gesture and mixed interaction modes. However, the results also suggest that less interest was shown in the mixed interaction mode, which may indicate that further development is required to increase its appeal. The findings suggest that controller-based mode offers a better user experience than hand gesture or mixed interaction modes, which suggests that additional research is needed to improve and refine the mixed interaction mode, or consider what types of tasks are best suited for its use.

6.1.3.2 User Preference Questionnaire Findings

Overall, the participants preferred using controller-based mode to complete the tasks in the puzzle study, which was suggested by Boletsis and Cedergren (2019), in which the controller was seen to be the easiest to use, given users' familiarity. The results revealed that the hand gesture mode was the least favourably regarded compared to the other two modes. However, it is essential to note that while controller-based mode is the most popular choice among participants, a significant portion of the participants still prefers a mixed interaction or hand gesture mode. This suggests that people can use multiple input methods to maximise their VR experience. Overall, there is still a market for more advanced interaction modes and that designers should consider incorporating these technologies into their VR experiences.

6.1.3.3 TLX Questionnaire Findings

Performance, productivity, and mental workload were evaluated using the TLX approach, which allows participants to provide subjective ratings of their feelings, opinions, and attitudes regarding the events (Nemoto & Beglar, 2014; Taherdoost, 2019). This approach presents participants with a series of statements to assess the levels of agreement and disagreement with the events in question.

The results of this study indicated that the mental workload associated with the controller-based mode was significantly lower than that of the hand gesture and mixed interaction modes. Additionally, participants reported perceiving a more significant challenge with the hand gesture and mixed interaction modes than with the controller-based mode. These findings align with the studies conducted by Park et al. (2017) and Xu et al. (2006), who suggested that users need some level of expertise when working with gestural commands before applying them to a scenario. Therefore, users should be given more time for preparation before interacting with the user study to ensure effective performance.

6.1.4 Talk-aloud Verbal Discussion

The results of this study demonstrate that the mixed interaction mode can potentially be a valuable and intuitive way of interacting with virtual environments. Participants generally expressed positive attitudes towards the mixed interaction mode, suggesting that it is a viable option to consider when developing new interaction modes. The findings also highlight certain advantages and disadvantages that should be considered when designing and developing mixed interaction mode. The advantages of the mixed interaction mode include its intuitive and natural feel, ability to improve task performance, and potential to reduce fatigue. The participants found the mixed interaction mode easy to learn and use, with most of them expressing that they felt comfortable using the system within a short time.

Furthermore, the participants reported that the mixed interaction mode had the potential to reduce fatigue and improve task performance, making it a suitable option for use in extended periods of use. This is consistent with the results of Mendes et al. (2014) and Song et al. (2012), both of whom noted that the hand gesture mode was perceived as more pleasing and informal compared to the controller-based mode for mid-air interactions. Meanwhile, Rantamaa et al. (2022) proposed a mechanical redesign of the controllers to minimise the uneasiness and fatigue caused from bulky controllers. The mixed interaction mode approach serves as a potential solution as it combines both the controller and hand gesture modes, and its utilisation of single-handed control may help reduce the amount of stress exerted on the hands and wrists, thus extending its usability.

On the other hand, the disadvantages of the mixed interaction mode include its potential to cause fatigue and confusion and its requirement for more practice and refinement. Some participants found the mixed interaction mode tiring and challenging to use, suggesting that more practice and refinement are needed. The participants also expressed confusion over the various input and output modalities, which could lead to incorrect operations. As suggested by Martin et al. (2022), incorporating multiple modalities can create an intuitive experience. However, the mixed interaction mode in the puzzle study has not yet achieved this ideal experience. This underscores the need for further development and user studies to fully realise the potential of the mixed interaction mode.

Finally, it is also worth noting that the use of a talk-aloud protocol during the study may have influenced participants' performance and task completion times. The limitations will be discussed further in Section 6.1.6.

6.1.5 Data Triangulation

In the puzzle study, data triangulation was utilised to strengthen the reliability of the findings by integrating multiple data sources. Qualitative insights were gathered through the talk-aloud protocol, where participants verbalised their thoughts and experiences while engaging with the VR puzzles. This method provided rich contextual information regarding participants' cognitive processes, such as how they approached solving the puzzles, their thought patterns when encountering challenges, and their decision-making strategies, offering valuable insight into their problem-solving processes during the interactions

The combination of qualitative and quantitative data allowed for a better understanding of user interactions. For instance, while performance metrics indicated efficiency in the mixed interaction mode, with Participant 24 achieving consistently fast completion times, qualitative feedback revealed instances of confusion. Participant 8 found the lack of a physical controller with hand gesture mode unusual. Despite this, the participant achieved better task completion times in Puzzle 1 and 3, which shows that even efficient modes can still provoke uncertainty among users.

Furthermore, data triangulation helped identify trends in user behaviour. Several participants preferred using both hands in the mixed interaction mode, suggesting a more intuitive interaction experience. However, others opted for one-handed use, particularly with hand gesture mode, where Participant 17 noted that the weight of the controller impacted their performance. This contrasts with the questionnaire data, which indicated that participants found the controller-based mode more tiresome, despite achieving better task completion times in some cases. This phenomenon mirrors findings from my previous research (Lee et al., 2020), where users reported dissatisfaction with controller-based mode despite better performance outcomes.

A closer examination of task completion times reveals further insights into participant experiences. For instance, Participant 3 found the controller better for some movements, while others were better with their own hands. This participant performed better in Puzzle 2 and 3 using hand gesture mode. Similarly, Participant 8, who found the lack of a physical controller with hand gesture mode unusual, yet still completed tasks quickly with hand gesture, achieving notable times in Puzzle 1. In contrast, Participant 30, who reported fatigue with the controller, had longer completion times using hand gesture in puzzles that required multiple resets, such as Puzzle 2. This indicates that despite the reported fatigue with the controller-based mode, hand gesture mode posed more significant challenges for this participant.

These insights underscore the importance of providing flexible interaction options to accommodate diverse user preferences and strategies. The apparent discrepancy between performance metrics and user satisfaction highlights the need for further research to understand user experiences with mixed interaction and controller-based modes. It is crucial to investigate why users may achieve better results with a specific interaction mode while simultaneously expressing a preference for alternatives.

6.1.6 Limitations

While the puzzle study provides valuable insights into the effectiveness of the mixed interaction mode in virtual reality, several limitations should be acknowledged to contextualise the findings within established HCI literature:

1. **Sequence Influence**: Those who encountered certain puzzles later in the study may have benefitted from prior experience in solving the puzzles in the first interaction mode. Once a puzzle was solved in the first mode, participants already knew how to approach it, which likely led to faster task completion times in subsequent modes. This learning effect could have influenced the results, as familiarity with the task rather than the interaction mode itself might account for improved performance. Axelsson et al. (2001) discussed similar effects in comparative studies of virtual and real environments, highlighting how prior exposure can impact problem-solving strategies.
2. **Cognitive Load and Task Design**: The cognitive load associated with the puzzle tasks may have influenced participant performance. High cognitive load can reduce task efficiency, particularly when users must manage multiple interaction modes. Ayres et al. (2009) suggested that instructional animations can help mitigate cognitive overload in hand manipulative tasks, which may be a consideration for future implementations. Additionally, Chang et al. (2020) highlighted that virtual reality sickness and cognitive strain can further impact user experience, an aspect relevant to this study.
3. **Volunteer and Response Bias**: The participants in this study were volunteers, which may limit the generalisability of the findings. Volunteers might be more interested in VR or have more prior experience with it, which could positively influence both their task performance and subjective assessments of the interaction modes. This bias could result in more favourable evaluations of the mixed interaction mode compared to a more general user population. Bekhet and Zauszniewski (2012) noted that methodological triangulation can help address such biases by integrating diverse data sources. Additionally, participants may have been inclined to provide responses they perceived as favourable, which can affect the reliability of subjective measures.
4. **Sample Representation**: The participants may not represent all potential users of VR systems. Factors such as age, level of technical expertise, and prior experience with VR systems can greatly influence both task performance and user experience. Consequently, the findings may not be applicable to all user groups, particularly those with less experience or different cognitive and motor abilities. Prior research, such as Juan et al. (2023), suggested that differences in user familiarity can significantly influence VR task performance.
5. **Uncontrolled Variables**: Several uncontrolled variables, such as prior exposure to similar tasks, user hand dominance, and individual differences in spatial ability, may have influenced participant performance. Neamoniti and Kasapakis (2022) highlighted the impact of such

variables on virtual interaction accuracy, suggesting that future studies should implement stricter control measures or larger sample sizes to mitigate these effects.

6. **Talk-Aloud Protocol Confound**: The use of a talk-aloud protocol during task completion introduces a notable confound to the research design. While this method provides valuable insights into participants' thought processes, it may inadvertently interfere with task performance by increasing cognitive load. Verbalising thoughts while solving puzzles demands additional mental effort, which could slow task completion times and affect interaction accuracy. Consequently, the task efficiency data might reflect the influence of the talk-aloud protocol rather than the genuine impact of the mixed interaction mode. This confound warrants careful consideration during data analysis, as it has the potential to skew the interpretation of performance results. Fonteyn et al. (1993) discussed how verbalisation during problem-solving can alter cognitive processing, potentially affecting task completion times. Similarly, Gill and Nonnecke (2012) examined the impact of verbal protocols on user experience evaluation, suggesting that such methods may interfere with natural interaction behaviours.
7. **Environmental and Technological Factors:** External factors such as variations in lighting, room setup, and the calibration of the VR equipment may have affected participants' performance. Technical issues with the Leap Motion tracking device were observed, which could have influenced the usability and accuracy of the interaction mode, particularly in tasks requiring precise manipulation. Previous studies (Neamoniti & Kasapakis, 2022) have also reported tracking precision challenges, particularly for fine motor tasks, highlighting the need to consider hardware limitations when interpreting the results.

These limitations indicate areas for further research, particularly in refining experimental design to control for confounding variables and integrating more diverse participant samples. Future studies should explore long-term user adaptation and conduct larger-scale experiments to validate the findings in broader contexts.

6.2 Cockpit Study

The cockpit study, conducted with a limited number of participants, provided initial insights into the potential benefits of the mixed interaction mode in VR. Participants reported that the mixed interaction mode combining controller-based with hand gesture modes was comfortable and efficient. However, it is important to note that these findings are preliminary and based on a small sample size.

While participants reported a positive user experience with the mixed interaction mode, these findings should be interpreted with caution. The design of the tasks specifically set out to favour mixed interaction mode, but that does not mean that the insight is applicable to all tasks as the first study would show. Therefore, further research is needed to confirm these results and to explore the effectiveness of the mixed interaction mode in different contexts and with a broader range of users, including those with varying levels of VR experience.

The interview results indicate that the mixed interaction mode approach effectively supported user engagement and task completion within the given scenarios. The user experience of the mixed interaction mode was generally positive, with most participants enjoying the experience. The user interface was well-received, with participants finding it intuitive and easy to use. The results suggest that the mixed interaction mode can accommodate a wide range of users, including those with varying VR experience levels. Additionally, the results suggest that the mixed interaction mode effectively combines elements of both physical and VR environments, allowing users to access information and tasks in both environments without significantly compromising the user experience.

The analysis of the interviews revealed several key findings. Firstly, participants found the interaction task to be straightforward and intuitive. This is perhaps not surprising as the task was designed to be suitable to the mixed interaction mode. The results from the task indicated that most participants did not find it physically or mentally demanding. This contrasts with the findings of the puzzle study, which indicated the presence of physical demand when interacting with the hand gesture and mixed interaction mode compared to the controller-based mode. Overall, there is evidence that the mixed interaction mode can be utilised successfully in certain situations but maybe not in all cases.

Secondly, participants reported a high degree of satisfaction with the mixed interaction mode. They commented that combining the hand gesture and controller-based modes allowed for a more precise and natural interaction than using a single device type. Further comparative evaluation will be required to fully understand the advantages of mixed interaction mode.

Thirdly, participants identified potential for a wide range of applications that could benefit from this type of mixed interaction mode, primarily in gaming and training within VR. Finally, participants identified the advantages and disadvantages of using this type of mixed interaction mode. Advantages included improved accuracy and naturalness of interaction, as well as the ability to access more complex tasks with the combination of the two devices. Furthermore, participants suggested disadvantages, including confusion when switching between the two devices. The design should be customisable, and the system should be able to adapt to different user preferences.

Participants echoed the sentiment of Kang et al. (2020) about the importance of providing appropriate visual cues when performing object manipulation tasks. They reported feeling fatigued and uncertain when using the controller-based and hand gesture modes for such tasks, particularly in mid-air interactions. These findings emphasise the importance of providing effective visual cues, such as changes of colour, to orient the users' movements and reduce user fatigue when using the controller-based or hand gesture. Moreover, using mixed interaction mode can reduce the overall weight of handheld devices, as the user only requires one controller instead of two. This reduction may provide greater stability and be less tiring for the user. While the mixed interaction mode shows potential in addressing some user fatigue by reducing the reliance on dual controllers, it is also possible that combining two interaction types may introduce new challenges, such as increased cognitive load or confusion from alternating between modes. This suggests that while mixed interaction mode offers benefits, further investigation is required to better understand and reduce any additional strain on users, especially during complex tasks.

Taking into account Huang et al.'s (2021) research, their qualitative evaluation of the user experience indicated potential application areas for the new mode of interaction. This research expands on Huang's work by extending the evaluation beyond game-like tasks to explore the effectiveness of hybrid inputs in other domains, providing a more comprehensive understanding of the usability, efficiency, and user satisfaction associated with hybrid inputs across diverse contexts.

In conclusion, while the results from the cockpit study suggest that the mixed interaction mode may offer several advantages over a single interaction mode, these findings are preliminary and should be confirmed through further research. The actual contributions of this research lie in its exploration of the mixed interaction mode in VR and its potential to inform future design decisions related to VR controller usage. The findings should be considered in light of the study's limitations, including the small sample size and the potential influence of the study's design on the results. The research has also identified areas for future exploration, such as the need for further comparative evaluation of mixed interaction mode and the potential for a wide range of applications that could benefit from this type of mixed interaction mode. This research has contributed to the ongoing development of knowledge regarding mixed interaction mode in VR and has provided a foundation for future studies in this area.

6.2.1 Data Triangulation

The cockpit study focused solely on qualitative data, gathering participants' experiences and perceptions through interviews after they completed tasks. Participants provided detailed feedback on the effectiveness of the mixed interaction mode, highlighting aspects such as the intuitiveness of switching between hand gestures and controller-based mode use, as well as their feelings of engagement or frustration.

To triangulate these qualitative findings with data from the puzzle study, insights from the cockpit study interviews were compared with both the performance metrics and qualitative feedback obtained in the puzzle study. For example, participants in the puzzle study verbalised their experiences during the talk-aloud protocol, highlighting usability challenges and preferences for interaction modes. Participants in the cockpit study reported confusion over control navigation while using the mixed interaction mode, which was also reflected in the puzzle study's qualitative data, where participants noted usability issues during puzzle-solving tasks. This direct comparison confirmed that the mixed interaction mode, while effective in simpler tasks, presented usability challenges in more complex environments.

Specific themes also emerged from the cockpit study interviews, such as the importance of user adaptability and flexibility in control methods. Participants indicated that while the mixed interaction mode was appreciated, some felt overwhelmed by the number of options available, particularly in complicated tasks within the cockpit study. This feedback paralleled insights from the puzzle study, where some participants also expressed confusion with the controls, underscoring the need for clearer guidance or streamlined interactions.

6.2.2 Limitations

Similarly, while the cockpit study builds upon the insights from the puzzle study and explores user experiences in a different context, it also has its own set of limitations:

1. **Limited Context**: The study was conducted in a specific cockpit context, and the findings may not generalise to other VR environments or tasks. For example, the tasks and interactions in a cockpit simulator might be quite different from those in a VR game or a virtual training program for a physical skill.

2. **Small Sample Size**: The number of participants in the study was relatively small, which may limit the statistical power and generalisability of the findings. A larger sample size could provide more robust results and allow for more detailed analyses, such as examining differences between subgroups of participants.
3. **Short-term Study**: The study was conducted over a short period of time, and it does not provide information on how user performance and experiences might change over time with continued use of the mixed interaction mode. Long-term studies could provide insights into how users adapt to the mixed interaction mode over time and whether initial advantages or disadvantages persist.
4. **Potential Learning Effects**: Participants' performance may have improved over time simply due to practice or familiarity with the VR environment and tasks, rather than the effectiveness of the mixed interaction mode.
5. **User Experience Measures:** The study relied on self-reported measures of user experience, which can be subjective and may not accurately reflect actual user experience. Future studies could benefit from including more objective measures of user experience, such as physiological measures or performance metrics.
6. **Participant Demographics and Task-Environment Mismatch**: The study participants lacked piloting experience, yet they were placed in a highly detailed virtual cockpit environment with specialised tasks. This mismatch between the complexity of the environment and the participant cohort may have influenced the results, as participants were primarily focused on interaction mode differences rather than authentic cockpit operations. If future research aims to extend this work with actual pilots, noting this limitation here provides a link to addressing it in future work.

Future research should aim to address these limitations, for example by using a counterbalanced design to control for sequence influence, recruiting a more diverse participant sample, conducting long-term studies, and considering additional variables that might influence task performance and user experience in VR.

6.3 Research Question

This section aims to answer the research question by synthesising findings from both the puzzle study and the cockpit study. The research question is:

> **RQ**: Under what circumstances does the mixed interaction mode provide advantages for object manipulations in virtual reality compared to traditional interaction modes?

In the puzzle study, there was a discrepancy between actual performance and perceived performance. Participants were unfamiliar with hand gesture mode, with only half having used the controller-based mode before, provided insights into the mode's efficacy. While the task completion time results and questionnaire findings were not entirely conclusive due to participants' unfamiliarity with hand gesture and the controller-based modes, the study highlighted the importance of considering hand gesture and controller-based modes when manipulating objects. Specifically, the controller and mixed interaction modes proved most efficient for tasks like rotating and docking, surpassing hand gesture in precision and accuracy. Additionally, the use of both hands during mixed interaction mode indicated potential for a more intuitive and engaging user experience. However, users who were new to hand gesture or mixed interaction modes faced challenges, suggesting a higher cognitive load. This underscores the critical role of cognitive skills in determining the effectiveness of mixed interaction mode in VR.

The cockpit study offered additional insights into user experience with mixed interaction mode in a more complex, context-specific setting. Participants generally found the mixed interaction mode more natural and immersive, which could enhance user experience in simulated scenarios. The study results highlight the potential of mixed interaction mode to improve user experience in VR applications. According to Frank and Kapila (2017), a mixed reality interface seeks to unify physical and digital realities by creating seamless transitions between them and allowing the co-existence and interaction of real and virtual objects and environments in real-time. This aligns with the cockpit study's findings, which highlight the potential of mixed interaction mode to improve user experience in VR applications tailored to its specific capabilities.

The results of the studies discussed herein support the multimodality notion proposed by Yang et al. (2019), which suggested that incorporating multiple sensing methods enables users to interact more naturally and efficiently. This aligns with the aim of improving user experience in VR applications through the exploration of mixed interaction mode.

Despite these promising outcomes, challenges remain, including physical strain, possible confusion from handling multiple interaction modes, and a potential need for user training. The findings indicate that the mixed interaction mode offers several advantages. Participants found it to be more intuitive and natural compared to traditional modes, as the combination of hand gesture and controller-based modes facilitated smoother interactions. In certain tasks, this approach improved task performance by reducing completion time and increasing precision. In certain tasks, this approach improved task performance by reducing completion time and increasing precision. Additionally, the mixed interaction mode provided flexibility in interaction, which contributed to a higher level of engagement and immersion in the virtual environment. These advantages suggest that mixed interaction mode can enhance VR usability by addressing both efficiency and user experience considerations.

6.4 Design Guidelines

This research aims to contribute to the understanding and interpretation of VR interaction design by developing new insights and applications from existing knowledge. The goal is to inform future decisions in VR interaction design through the development of design guidelines. These guidelines provide a better understanding of best practices for a mixed interaction mode, which can be used to develop more efficient and user-friendly applications.

The increasing use of technology in everyday life underscores the importance of understanding how users prefer to interact with a system. This understanding allows designers to create interfaces that are easier to use and more intuitive. In this context, the design of the systems and their usability become paramount. Bossavit et al. (2014) emphasised that appropriate design decisions significantly impact usability outcomes. Therefore, designers should consider providing users with multiple interaction modes for object manipulation tasks in a virtual environment and how to design for mixed interaction mode.

Building on the work of Huang et al. (2021), which evaluated user experiences across three modes of interaction: controller-based, hand gesture, and a mixed interaction mode combining a single controller-based with hand gesture modes, this research extends the evaluation to different VR interaction tasks to investigate their potential impacts on user performance, engagement, and experience.

The following design guidelines, informed by both Huang et al.'s work and the findings of this research, are proposed:

- **Flexible Interaction Options:** Design systems that allow for flexibility in the use of interaction modes. Rather than predetermining which hand uses the controller-based or hand gesture, consider designing systems that can adapt to the user's preferences dynamically during tasks. This flexibility can accommodate different user strategies and preferences, as observed in the puzzle study where participants predominantly used both hands during mixed interaction mode (see Section 4.2.1: Participant Use of Hand(s) Measures). This approach moves away from static interaction modes and towards a more dynamic and adaptable system. In line with the suggestion of Olmedo et al. (2015), they highlighted the need for standardised multimodal systems to enhance usability and accessibility.

- **Extended Training Phase:** Allocate participants an extended duration for training to familiarise themselves with the manipulation tasks using both the controller-based and hand gesture modes. This prolonged training phase aids in reducing cognitive load and enhancing task performance. This need was highlighted in questionnaire responses, where participants faced challenges adjusting to new interaction modes (see Section 6.1.3: Questionnaire Discussion). As suggested by Kang et al. (2020), improved tutorials or visual cues can aid in effectively using hand gesture before transitioning to mixed interaction mode. This approach promotes greater user engagement and a more intuitive user experience.

- **Real-World Behaviour Alignment:** Consider how simulated scenarios will fit into the design. For instance, in the cockpit study, participants found that using the controller as the control stick and hand gestures to turn the knobs was simple and straightforward, closely mirroring real-world experiences. This was discussed in the interview findings (see Section 5.2.2: Interview). This alignment with real-world behaviour highlights the advantage of directly mapping real-world behaviours to VR interactions, enhancing the intuitiveness and efficiency of the system.

- **Visual Cues:** Use appropriate visual cues for object manipulation tasks to help users understand the available interactions. Participants highlighted the need for visual cues, such as the hover effect from hand gesture mode, to help users keep track of their progress and provide feedback on their performance. Participants noted the need for clearer visual cues to aid interaction (see Section 4.2.3: Questionnaire and Section 4.2.4: Talk-aloud Verbal Summary). This can be particularly beneficial when there is no haptic feedback, as users often look for visual cues in such scenarios. Therefore, the effective use of visual indicators can mitigate the lack of physical feedback in VR, improving task accuracy and user confidence.

- **Interaction Mode Selection Based on Task Complexity:** The selection of the interaction mode should be based on the complexity of the task. For complex tasks that require precise control and stability, such as manipulating virtual objects or operating control panels, the controller-based mode is more suitable. On the other hand, the hand gesture mode excels in enabling quicker object rotation, as mentioned by the participants in the puzzle study (see Sections 4.2.2 Task Completion Time). Designing systems to match interaction modes with task requirements will enhance performance and user satisfaction.

- **User Comfort and Physical Demand Considerations:** When designing interaction modes, consider the physical demands and comfort of the users. For instance, while the controller-based mode demonstrated good performance in tasks involving grasping and placing objects, it was physically tiring due to its weight. This was also mentioned by the participants during the cockpit study (see Section 5.2.2: Interview). Moreover, using a controller for extended periods can cause fatigue and discomfort, while it also strains the user's hands and wrists over time (Lou et al., 2022). Therefore, minimising the weight of devices and allowing for breaks in interaction will reduce discomfort and enhance long-term usability.

These guidelines are directly informed by the findings of this research and represent a critical contribution to the evolving field of mixed interaction mode in VR. Whilst they are informed by this research, they do need to be viewed as somewhat propositional, and their general applicability needs to be confirmed through future research. By serving as a foundation for future research, they not only enhance the understanding of how mixed interaction mode can improve user experience but also provide actionable strategies for designers seeking to implement these interactions effectively. Importantly, these guidelines highlight the necessity of considering user preferences and needs, thereby ensuring that VR applications are intuitive and engaging. The emphasis on integrating user feedback into the design process is crucial for creating adaptive systems that can evolve with user behaviour and technological advancements.

Chapter 7: Conclusions

This research contributes to the understanding of interaction modes in VR by examining the opportunities presented by a mixed interaction mode, which combines controller-based and hand gesture interaction modes. While traditional VR interfaces typically rely on either controller-based or hand gesture modes, this study explores the benefits and limitations of integrating both. Through two user studies, focused on puzzle-solving and cockpit control tasks, valuable insights have been provided, although the findings should be considered within the limitations of the research.

7.1 Contribution

The primary contribution of this research lies in its exploration of the potential of a mixed interaction mode. The combination of controller-based and hand gesture modes offers an alternative to traditional single-mode interaction methods for certain tasks, particularly those requiring both precision and flexibility. The mixed interaction mode approach can enhance user flexibility by allowing smoother transitions between fine motor tasks and broader object manipulations.

However, these findings are exploratory rather than definitive. The user studies suggest opportunities for improvement in task performance, but these advantages are task-specific and are limited to the contexts examined within the puzzle and cockpit scenarios. Generalising these results to broader VR applications would be premature. Therefore, while this research provides insightful evidence regarding the mixed interaction mode, further studies are necessary to fully assess its applicability across more diverse environments.

The design guidelines derived from these insights represent an important step forward. They offer preliminary considerations for VR designers looking to implement a mixed interaction mode, though these recommendations should be seen as evolving and subject to refinement through future research and validation.

7.2 Limitations

The limitations of each study are detailed in prior chapters, with specific attention to Sections 6.1.6 and 6.2.2. However, it is important to acknowledge several overarching limitations when interpreting the findings presented in this work. The user studies were conducted with a relatively small sample size and limited participant diversity, which may affect the generalisability of the results. Furthermore, the use cases of puzzle-solving and cockpit control are relatively controlled and simplified scenarios, which may not reflect the complexity of real-world VR applications.

There were also technical challenges during the studies, particularly with the Leap Motion hand tracking system. These issues may have impacted user performance, potentially skewing the data. Furthermore, the study did not investigate long-term effects such as user fatigue, which could become relevant when using mixed interaction mode for extended periods or in more demanding tasks.

Additionally, the study's focus on usability and user satisfaction, while informative, does not provide a comprehensive assessment of system performance in more complex or professional environments. Future work could include pilots as actual domain users, as this would allow a more realistic evaluation of the mixed interaction mode's effectiveness in a real-world setting with complex tasks. However, working with pilots presents unique challenges, such as their specialised skill sets, time constraints, and safety concerns, which would require careful consideration and planning. These challenges justify this as an area for future research but fall outside the scope of the current study. Therefore, the results should be viewed as preliminary insights rather than conclusive evidence of the mixed interaction mode's effectiveness.

7.3 Future Work

Future research should focus on extending the exploration of the mixed interaction mode to a wider range of contexts and more complex tasks. One area of opportunity is the integration of additional sensory inputs, such as haptic feedback, voice commands, and eye-tracking, which could further enhance immersion and interaction efficiency in VR environments. The cockpit study showed that participants perceived a better experience with the interaction mode in a scenario designed to leverage the potentials it offers. However, this study was qualitative, and there is a need to verify this potential through a quantitative research study that compares the mixed interaction mode with other options on this type of task.

Expanding the participant pool and increasing the sample size in future studies would also provide a more comprehensive understanding of how different user groups respond to mixed interaction mode. Including users with various levels of VR experience, different age groups, and individuals with physical disabilities could offer a broader perspective on the strengths and limitations of this interaction method. Some of the limitations of this study, such as the learning effect and sequencing of tasks, would be better addressed in a larger scale study.

Further studies should also consider the long-term effects of the mixed interaction mode, particularly in terms of user fatigue and performance over extended periods. In addition, technological advancements in hand tracking systems and VR hardware will likely address some of the technical issues encountered in this study, enabling more accurate data collection and user analysis.

7.4 Conclusion

In conclusion, this research provides insightful evidence into the opportunities presented by the mixed interaction mode in VR, particularly for tasks involving object manipulation. While the findings suggest that combining controller-based and hand gesture modes can enhance user experience and task performance, these insights are limited to the specific contexts explored in this study. The proposed design guidelines offer a valuable starting point for VR designers but require further refinement and validation through additional research.

Although preliminary, these contributions open new avenues for further investigation into the use of the mixed interaction mode across a wider range of VR applications. Addressing the identified limitations and building on the current findings can drive future developments in VR interaction design, ultimately enhancing user experiences across various fields.

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Appendices

Appendix 1: Task completion time in seconds

	Controller-based			Hand Gesture			Mixed		
	Puzzle 1	Puzzle 2	Puzzle 3	Puzzle 1	Puzzle 2	Puzzle 3	Puzzle 1	Puzzle 2	Puzzle 3
User 1	25	62	63	11	80	26	31	45	28
User 2	20	30	15	17	63	65	22	39	27
User 3	38	103	21	40	45	16	26	115	19
User 4	64	44	17	34	70	18	35	37	25
User 5	163	34	20	48	64	25	46	70	24
User 6	33	26	17	12	49	32	7	50	20
User 7	17	64	56	16	64	34	27	40	20
User 8	40	52	60	16	127	43	15	182	36
User 9	53	50	172	43	110	22	25	108	28
User 10	54	51	28	24	100	25	29	59	11
User 11	25	88	20	22	125	34	17	40	38
User 12	57	66	35	26	134	43	20	63	33
User 13	33	55	12	17	176	29	26	96	28
User 14	35	38	36	16	57	32	13	39	19
User 15	26	38	6	27	124	23	72	131	25
User 16	45	89	72	18	99	19	12	61	14
User 17	17	33	14	33	77	17	11	70	17
User 18	44	85	39	54	149	78	25	69	40
User 19	146	34	13	24	161	30	16	45	29
User 20	43	32	12	16	60	39	14	40	37
User 21	60	34	15	41	79	17	17	67	11
User 22	34	80	20	46	165	29	30	68	60
User 23	56	42	40	12	108	63	36	44	41
User 24	90	49	65	27	148	59	12	54	17
User 25	17	29	26	14	58	13	7	49	18
User 26	22	25	13	13	56	17	6	23	10
User 27	61	95	57	20	62	32	62	39	27
User 28	51	106	124	39	216	53	53	27	10
User 29	25	84	122	33	147	33	56	27	13
User 30	33	82	74	18	248	62	34	66	30
User 31	75	175	91	18	179	64	15	172	19
User 32	78	145	23	46	132	84	30	113	28
User 33	32	77	13	29	58	33	32	75	22
User 34	44	96	31	44	74	70	16	46	13
User 35	171	69	33	54	232	25	21	157	88
User 36	21	36	11	9	103	45	6	65	9
User 37	26	27	16	24	73	23	7	57	11
User 38	22	44	18	13	66	89	17	40	11
User 39	13	53	14	19	75	14	20	32	10
User 40	11	44	57	19	104	16	19	83	39

Appendix 2: Friedman tests for task completion time across three interaction modes

Puzzle 1

Friedman's Test	
Alpha	0.05
Q-stat	17.477707
df	2
p-value	0.0001602

Puzzle 2

Friedman's Test	
Alpha	0.05
Q-stat	30.72956
df	2
p-value	0.00000021

Puzzle 3

Friedman's Test	
Alpha	0.05
Q-stat	8.3164557
df	2
p-value	0.0156352

Appendix 3: Post hoc tests for task completion time

Puzzle 1 (JASP) with Bonferroni correction

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	3.161	78	101.000	73.000	0.002	0.007	0.004
	Mixed	3.951	78	101.000	66.000	1.695×10^{-4}	5.085×10^{-4}	5.085×10^{-4}
Leap Motion	Mixed	0.790	78	73.000	66.000	0.432	1.000	0.432

Note. Grouped by subject.

Puzzle 2 (JASP) with Bonferroni correction

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	4.935	78	64.500	108.500	4.442×10^{-6}	1.333×10^{-5}	1.333×10^{-5}
	Mixed	0.280	78	64.500	67.000	0.780	1.000	0.780
Leap Motion	Mixed	4.655	78	108.500	67.000	1.307×10^{-5}	3.921×10^{-5}	2.614×10^{-5}

Note. Grouped by subject.

Puzzle 3 (JASP) with Bonferroni correction

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	1.182	78	81.500	92.000	0.241	0.723	0.241
	Mixed	1.688	78	81.500	66.500	0.095	0.286	0.191
Leap Motion	Mixed	2.869	78	92.000	66.500	0.005	0.016	0.016

Note. Grouped by subject.

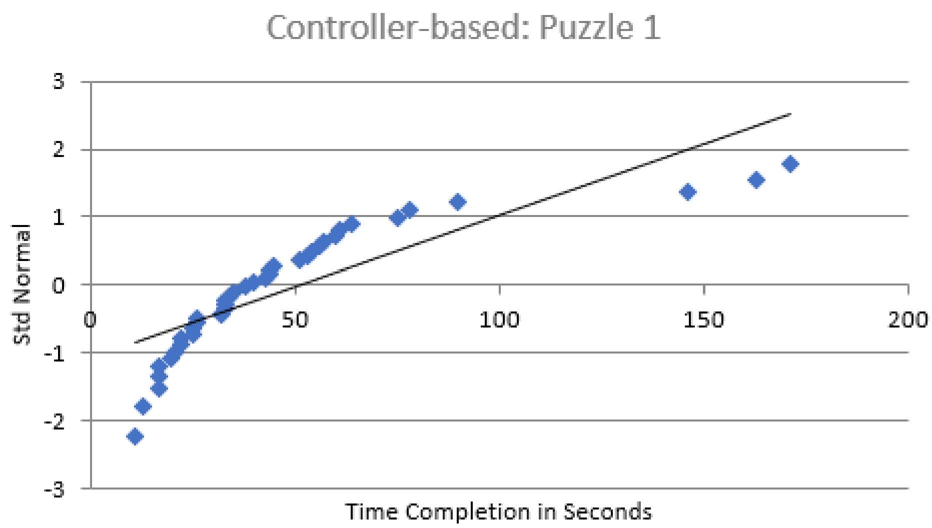
Appendix 4: Use of hand(s)

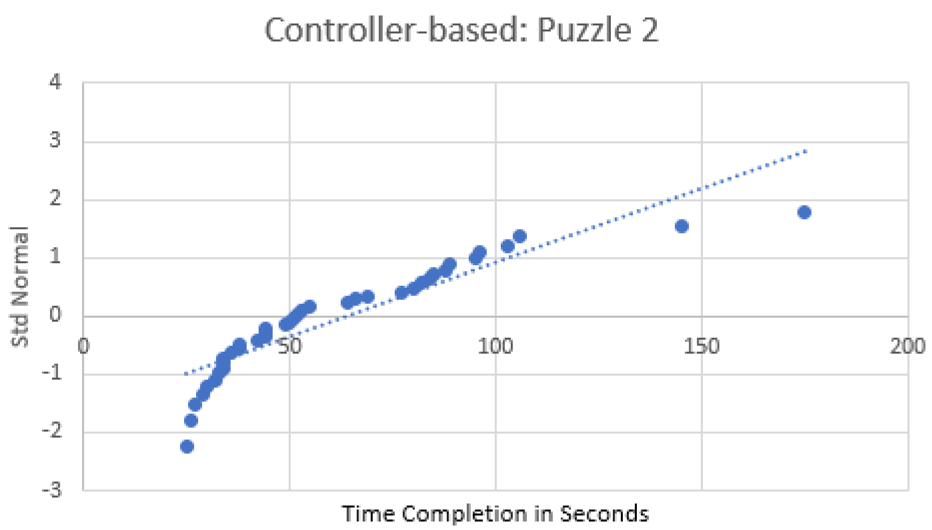
1 = Single hand, 2 = Both hands												
	Physical Puzzle			**Controller-based**			**Hand Gesture**			**Mixed**		
Puzzle	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
User 1	1	2	2	2	2	2	1	2	2	2	2	2
User 2	1	2	2	1	2	2	2	2	2	2	2	2
User 3	1	2	2	2	2	2	2	2	2	1	2	1
User 4	2	2	2	2	2	1	2	2	2	2	2	2
User 5	2	2	2	2	1	1	1	1	1	2	2	1
User 6	2	2	2	2	2	2	2	2	2	1	2	2
User 7	2	2	2	1	2	2	1	2	2	2	2	2
User 8	1	2	2	2	2	2	2	2	2	2	2	2
User 9	1	2	2	1	1	1	1	1	1	1	2	2
User 10	2	2	2	1	2	2	1	2	2	2	2	2
User 11	1	2	2	2	2	2	1	2	1	2	2	2
User 12	2	2	2	2	2	2	2	2	1	2	2	1
User 13	1	2	2	1	1	1	1	1	1	2	2	2
User 14	1	2	2	2	2	2	2	2	2	2	2	2
User 15	2	2	1	2	2	2	2	2	2	2	2	2
User 16	1	2	2	2	2	2	2	2	2	2	2	2
User 17	2	2	2	2	2	2	2	2	2	2	2	2
User 18	2	2	2	2	2	2	1	1	1	2	2	2
User 19	1	2	2	1	1	1	1	1	1	1	2	2
User 20	1	2	2	1	2	2	1	2	2	2	2	2
User 21	1	2	2	2	1	1	1	2	2	2	2	2
User 22	2	2	2	2	2	1	1	2	1	2	1	1
User 23	2	2	2	1	1	2	2	2	2	2	2	2
User 24	2	2	2	2	2	1	2	2	2	2	2	2
User 25	2	2	2	1	1	1	1	1	1	1	2	2
User 26	2	2	2	1	1	1	1	1	1	2	2	2
User 27	2	2	2	1	2	1	2	2	2	2	2	2
User 28	2	2	2	2	2	2	2	2	2	2	2	2
User 29	2	2	2	1	2	2	2	2	2	1	1	1
User 30	2	2	2	1	2	2	1	2	2	2	1	1
User 31	2	2	2	1	2	2	1	2	2	2	2	1
User 32	2	2	2	2	1	2	2	2	2	2	2	2
User 33	2	2	2	2	2	1	1	1	2	2	2	2
User 34	1	2	2	1	1	2	2	2	2	2	2	2
User 35	2	2	2	2	2	2	2	2	2	1	2	2
User 36	1	2	2	2	2	2	2	2	2	1	2	1
User 37	2	2	2	2	1	2	1	2	2	2	2	2
User 38	2	2	2	2	2	2	2	2	2	2	2	2
User 39	2	2	2	2	2	2	2	2	2	2	2	1
User 40	2	2	2	1	2	2	2	2	1	1	2	2

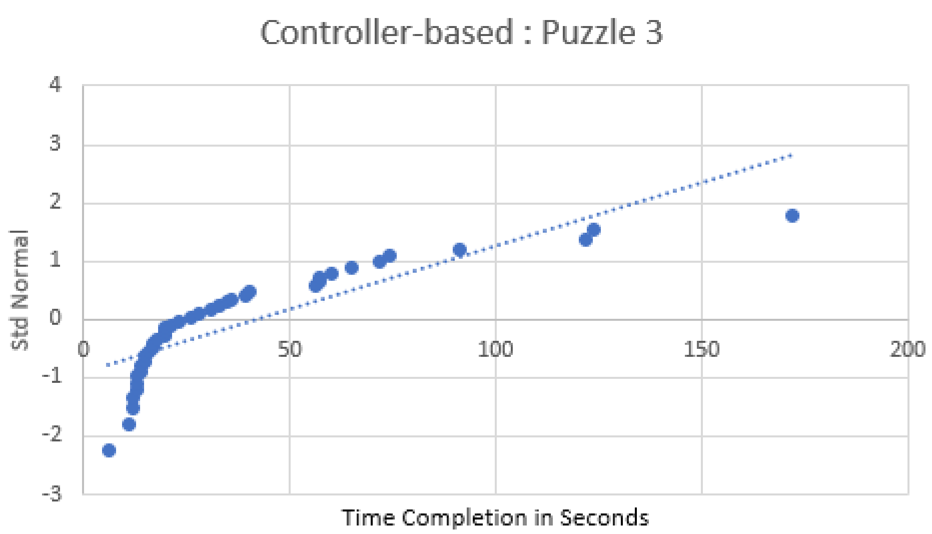
Appendix 5: Reset count

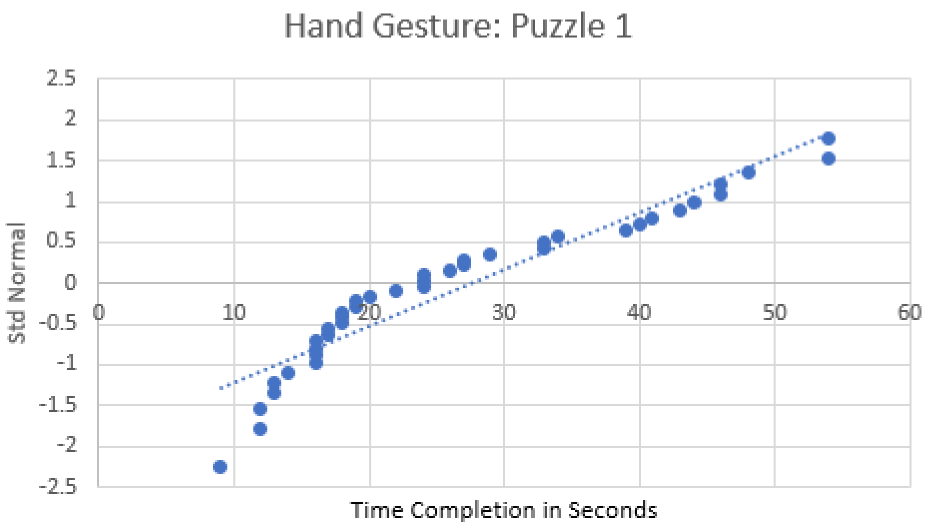
		Puzzle 2				Puzzle 3	
	Controller-based	Hand Gesture	Mixed		Controller-based	Hand Gesture	Mixed
User 1	0	0	0	User 1	0	0	0
User 2	0	1	0	User 2	0	1	0
User 3	0	0	1	User 3	0	0	0
User 4	1	0	0	User 4	0	0	1
User 5	0	0	0	User 5	0	0	0
User 6	0	0	0	User 6	0	0	0
User 7	0	0	1	User 7	0	0	0
User 8	0	0	1	User 8	0	0	0
User 9	1	0	1	User 9	0	0	0
User 10	0	0	1	User 10	0	0	0
User 11	1	0	0	User 11	0	0	0
User 12	0	1	0	User 12	0	0	0
User 13	0	0	0	User 13	0	0	0
User 14	0	0	0	User 14	0	0	0
User 15	2	0	0	User 15	0	0	0
User 16	0	0	0	User 16	0	0	0
User 17	0	0	0	User 17	0	0	0
User 18	0	1	0	User 18	0	0	0
User 19	0	0	1	User 19	0	0	0
User 20	1	0	0	User 20	0	2	0
User 21	0	0	0	User 21	0	0	0
User 22	0	0	0	User 22	0	0	0
User 23	0	0	2	User 23	0	0	0
User 24	0	0	0	User 24	0	1	0
User 25	0	0	0	User 25	0	0	0
User 26	0	0	0	User 26	0	0	0
User 27	0	0	0	User 27	0	0	0
User 28	0	1	0	User 28	0	6	0
User 29	0	0	0	User 29	0	0	0
User 30	0	2	0	User 30	0	0	0
User 31	0	0	0	User 31	0	2	1
User 32	0	0	0	User 32	0	0	0
User 33	0	0	0	User 33	0	0	1
User 34	2	3	0	User 34	0	2	0
User 35	0	0	0	User 35	0	0	1
User 36	0	0	1	User 36	0	0	0
User 37	1	0	0	User 37	0	0	0
User 38	1	4	2	User 38	1	4	0
User 39	0	2	0	User 39	0	0	0
User 40	1	0	0	User 40	2	0	1
TOTAL RESET COUNT	11	15	11	**TOTAL RESET COUNT**	3	18	5

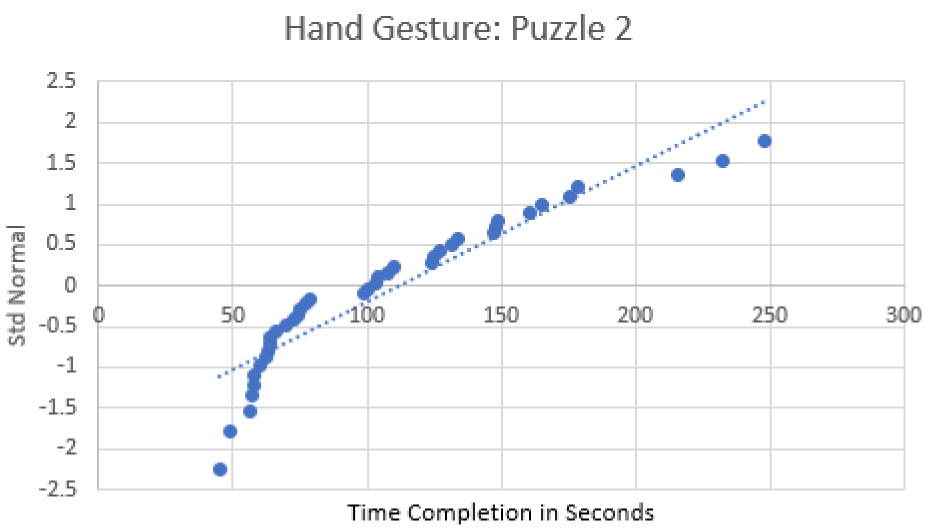
Appendix 6: Quantile-Quantile plots

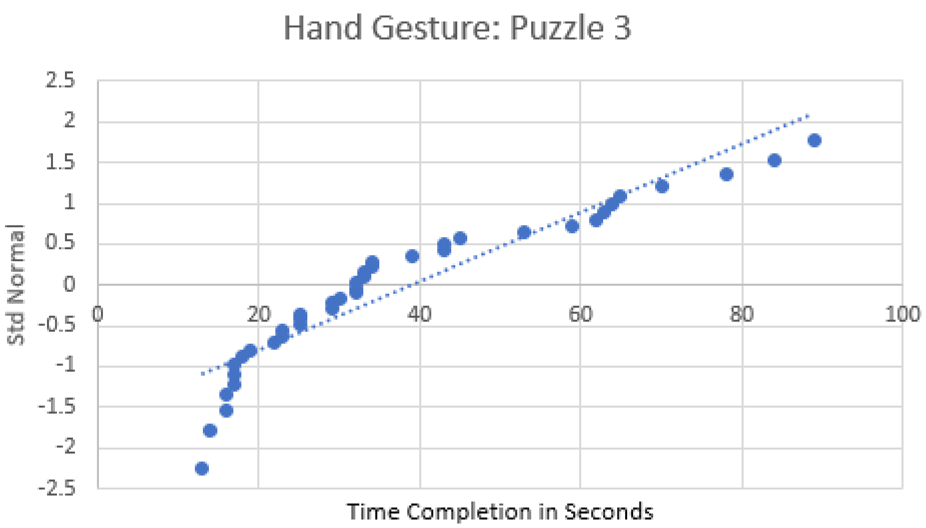


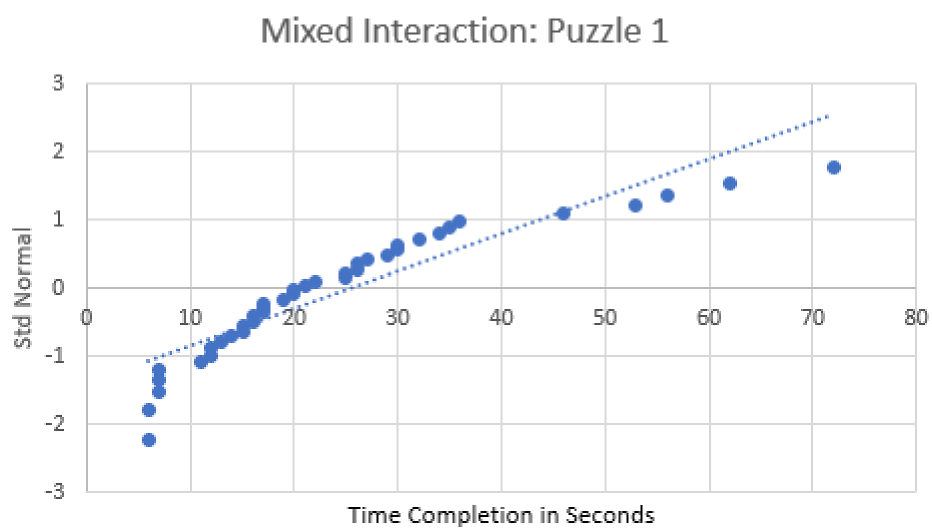


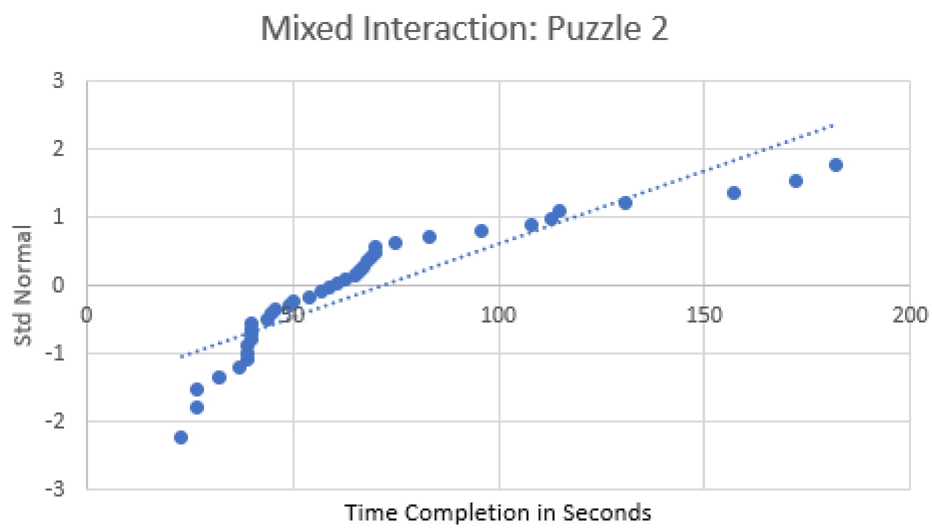


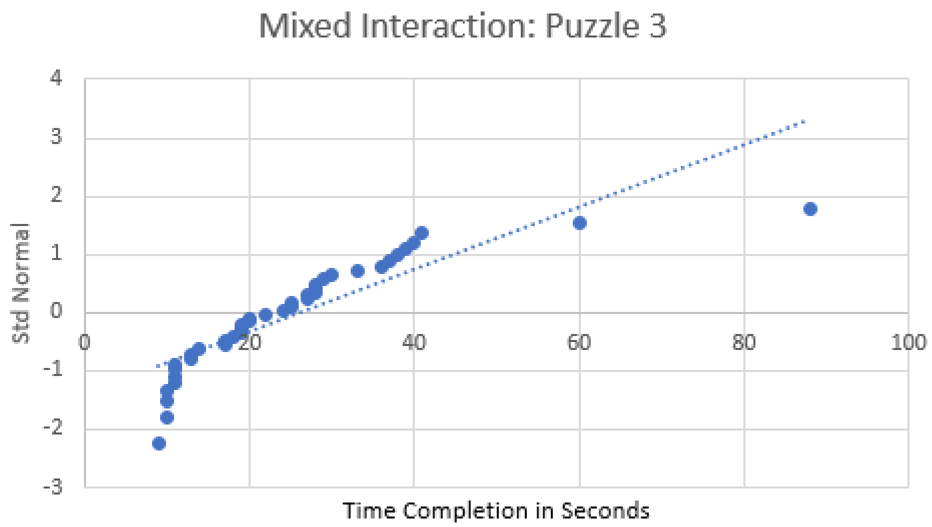

Hand Gesture: Puzzle 1
Std Normal
Time Completion in Seconds
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
10
20
30
40
50
60


Hand Gesture: Puzzle 2
Std Normal
Time Completion in Seconds
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
50
100
150
200
250
300


Hand Gesture: Puzzle 3
Std Normal
Time Completion in Seconds
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
20
40
60
80
100


Mixed Interaction: Puzzle 1
Std Normal
Time Completion in Seconds
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
60
70
80


Mixed Interaction: Puzzle 2
Std Normal
Time Completion in Seconds
3
2
1
0
-1
-2
-3
0
50
100
150
200


Mixed Interaction: Puzzle 3
Std Normal
Time Completion in Seconds
4
3
2
1
0
-1
-2
-3
0
20
40
60
80
100

Appendix 7: Participation questionnaire

Project title: ***Mixed Interaction: Evaluating User interactions for Object manipulations in Virtual Space***

Please answer the following questions that relate to your testing experience.

	Strongly Disagree		Agree		Strongly
1. I found the interaction mode was easy to use.					
Controller-based	**1**	**2**	**3**	**4**	**5**
Hand gesture	1	2	3	4	5
Mixed interaction	1	2	3	4	5
2. It was easy to learn to use the interaction mode.					
Controller-based	1	2	3	4	5
Hand gesture	1	2	3	4	5
Mixed interaction	1	2	3	4	5
3. The interaction mode is efficient.					
Controller-based	1	2	3	4	5
Hand gesture	1	2	3	4	5
Mixed interaction	1	2	3	4	5
4. I found it easy to select an object using the interaction mode.					
Controller-based	1	2	3	4	5
Hand gesture	1	2	3	4	5
Mixed interaction	1	2	3	4	5
5. I found it easy to move an object using the interaction mode.					
Controller-based	1	2	3	4	5
Hand gesture	1	2	3	4	5
Mixed interaction	1	2	3	4	5
6. I found it easy to rotate an object using the interaction mode.					
Controller-based	1	2	3	4	5
Hand gesture	1	2	3	4	5
Mixed interaction	1	2	3	4	5
7. I found it easy to dock an object using the interaction mode.					
Controller-based	1	2	3	4	5
Hand gesture	1	2	3	4	5

Mixed interaction	1	2	3	4	5

8. I would like to use the interaction mode frequently.

Controller-based	1	2	3	4	5
Hand gesture	1	2	3	4	5
Mixed interaction	1	2	3	4	5

9. I felt very confident using the interaction mode.

Controller-based	1	2	3	4	5
Hand gesture	1	2	3	4	5
Mixed interaction	1	2	3	4	5

10. The interaction mode was effective in helping me complete the tasks.

Controller-based	1	2	3	4	5
Hand gesture	1	2	3	4	5
Mixed interaction	1	2	3	4	5

11. It was enjoyable to use this interaction.

Controller-based	1	2	3	4	5
Hand gesture	1	2	3	4	5
Mixed interaction	1	2	3	4	5

12. For the tasks I was asked to do, I prefer this interaction style the most.

☐ Controller-based ☐ Hand gesture ☐ Mixed interaction

13. Overall, I prefer this interaction style the most.

☐ Controller-based ☐ Hand gesture ☐ Mixed interaction

14. How mentally demanding was the task?

Controller-based

Very Low Average Very High

Hand gesture

Very Low Average Very High

Mixed interaction

Very Low Average Very High

15. How physically demanding was the task?

Controller-based

Very Low Average Very High

Hand gesture

Very Low Average Very High

Mixed interaction

Very Low Average Very High

16. How successful were you in accomplishing what you were asked to do?

Controller-based

Perfect Average Failure

Hand gesture

Perfect Average Failure

Mixed interaction

Perfect Average Failure

17. How hard did you have to work to accomplish your level of performance?

Controller-based

Very Low Average Very High

Hand gesture

Very Low Average Very High

Mixed interaction

Very Low Average Very High

18. How insecure, discourage, irritated, stressed, and annoyed were you?

Controller-based

Very Low Average Very High

Hand gesture

Very Low Average Very High

Mixed interaction

Very Low Average Very High

Appendix 8: Friedman tests of questionnaires across three interaction modes

Question 1 Alpha 0.05 Q-stat 16.54545 df 2 p-value 0.000255	**Question 2** Alpha 0.05 Q-stat 9.26 df 2 p-value 0.009755	**Question 3** Alpha 0.05 Q-stat 18.20635 df 2 p-value 0.000111
Question 4 Alpha 0.05 Q-stat 19.96581 df 2 p-value 0.00005	**Question 5** Alpha 0.05 Q-stat 15.1405 df 2 p-value 0.000516	**Question 6** Alpha 0.05 Q-stat 2.904762 df 2 p-value 0.234012
Question 7 Alpha 0.05 Q-stat 13.23214 df 2 p-value 0.001339	**Question 8** Alpha 0.05 Q-stat 12.40909 df 2 p-value 0.00202	**Question 9** Alpha 0.05 Q-stat 9.153153 df 2 p-value 0.01029
Question 10 Alpha 0.05 Q-stat 12.74783 df 2 p-value 0.001705	**Question 11** Alpha 0.05 Q-stat 1.031579 df 2 p-value 0.597029	**Question 14** Alpha 0.05 Q-stat 19.95122 df 2 p-value 0.000047
Question 15 Alpha 0.05 Q-stat 8.99115 df 2 p-value 0.011158	**Question 16** Alpha 0.05 Q-stat 8.460432 df 2 p-value 0.014549	**Question 17** Alpha 0.05 Q-stat 21.14483 df 2 p-value 0.00003
Question 18 Alpha 0.05 Q-stat 15.6 df 2 p-value 0.00041		

Appendix 9: Post hoc test for questionnaires

Question 1

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	3.703	78	99.000	69.000	3.960×10^{-4}	0.001	0.001
	Mixed	3.333	78	99.000	72.000	0.001	0.004	0.003
Leap Motion	Mixed	0.370	78	69.000	72.000	0.712	1.000	0.712

Note. Grouped by subject.

Question 2

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	3.064	78	90.500	69.000	0.003	0.009	0.009
	Mixed	1.425	78	90.500	80.500	0.158	0.474	0.210
Leap Motion	Mixed	1.639	78	69.000	80.500	0.105	0.316	0.210

Note. Grouped by subject.

Question 3

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	4.109	78	99.000	66.500	9.739×10^{-5}	2.922×10^{-4}	2.922×10^{-4}
	Mixed	3.097	78	99.000	74.500	0.003	0.008	0.005
Leap Motion	Mixed	1.011	78	66.500	74.500	0.315	0.945	0.315

Note. Grouped by subject.

Question 4

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	4.466	78	98.000	64.000	2.652×10^{-5}	7.957×10^{-5}	7.957×10^{-5}
	Mixed	2.627	78	98.000	78.000	0.010	0.031	0.021
Leap Motion	Mixed	1.839	78	64.000	78.000	0.070	0.209	0.070

Note. Grouped by subject.

Question 5

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	3.744	78	97.000	68.000	3.449×10^{-4}	0.001	0.001
	Mixed	2.840	78	97.000	75.000	0.006	0.017	0.011
Leap Motion	Mixed	0.904	78	68.000	75.000	0.369	1.000	0.369

Note. Grouped by subject.

Question 7

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	3.426	78	95.500	70.000	9.786×10^{-4}	0.003	0.003
	Mixed	2.822	78	95.500	74.500	0.006	0.018	0.012
Leap Motion	Mixed	0.605	78	70.000	74.500	0.547	1.000	0.547

Note. Grouped by subject.

Question 8

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	2.962	78	96.500	72.500	0.004	0.012	0.008
	Mixed	3.147	78	96.500	71.000	0.002	0.007	0.007
Leap Motion	Mixed	0.185	78	72.500	71.000	0.854	1.000	0.854

Note. Grouped by subject.

Question 9

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	2.700	78	93.000	73.000	0.009	0.026	0.026
	Mixed	2.565	78	93.000	74.000	0.012	0.037	0.026
Leap Motion	Mixed	0.135	78	73.000	74.000	0.893	1.000	0.893

Note. Grouped by subject.

Question 10

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	3.314	78	95.500	70.500	0.001	0.004	0.004
	Mixed	2.850	78	95.500	74.000	0.006	0.017	0.011
Leap Motion	Mixed	0.464	78	70.500	74.000	0.644	1.000	0.644

Note. Grouped by subject.

Question 14

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	4.416	78	61.000	95.500	3.193×10^{-5}	9.579×10^{-5}	9.579×10^{-5}
	Mixed	2.880	78	61.000	83.500	0.005	0.015	0.010
Leap Motion	Mixed	1.536	78	95.500	83.500	0.129	0.386	0.129

Note. Grouped by subject.

Question 15

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	2.541	78	67.000	86.000	0.013	0.039	0.027
	Mixed	2.675	78	67.000	87.000	0.009	0.027	0.027
Leap Motion	Mixed	0.134	78	86.000	87.000	0.894	1.000	0.894

Note. Grouped by subject.

Question 16

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	2.884	78	69.000	93.000	0.005	0.015	0.015
	Mixed	1.082	78	69.000	78.000	0.283	0.848	0.283
Leap Motion	Mixed	1.803	78	93.000	78.000	0.075	0.226	0.151

Note. Grouped by subject.

Question 17

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	4.410	78	58.000	95.500	3.269×10^{-5}	9.806×10^{-5}	9.806×10^{-5}
	Mixed	3.352	78	58.000	86.500	0.001	0.004	0.002
Leap Motion	Mixed	1.058	78	95.500	86.500	0.293	0.879	0.293

Note. Grouped by subject.

Question 18

Conover Test

Conover's Post Hoc Comparisons - Time

		T-Stat	df	W_i	W_j	p	p_{bonf}	p_{holm}
Controller	Leap Motion	3.808	78	62.500	92.500	2.772×10^{-4}	8.315×10^{-4}	8.315×10^{-4}
	Mixed	2.856	78	62.500	85.000	0.005	0.016	0.011
Leap Motion	Mixed	0.952	78	92.500	85.000	0.344	1.000	0.344

Note. Grouped by subject.

Appendix 10: Questionnaire data

Question 1: I found the interaction mode was easy to use.

	Controller-based	Hand Gesture	Mixed
User 1	4	3	4
User 2	5	2	4
User 3	3	4	2
User 4	5	3	3
User 5	4	3	2
User 6	5	4	4
User 7	4	3	2
User 8	5	4	2
User 9	5	3	4
User 10	4	3	3
User 11	5	3	4
User 12	4	3	4
User 13	4	2	2
User 14	5	5	4
User 15	3	2	1
User 16	3	4	3
User 17	4	5	2
User 18	5	3	3
User 19	3	4	5
User 20	5	5	5
User 21	4	4	5
User 22	4	3	2
User 23	4	4	3
User 24	3	2	4
User 25	5	4	3
User 26	4	3	4
User 27	5	5	2
User 28	5	5	4
User 29	5	3	5
User 30	4	1	4
User 31	4	3	5
User 32	3	3	3
User 33	4	3	2
User 34	4	2	5
User 35	4	4	3
User 36	5	4	4
User 37	4	3	5
User 38	4	3	4
User 39	4	2	5
User 40	3	4	3

Question 2: It was easy to learn to use the interaction mode.

	Controller-based	Hand Gesture	*Mixed*
User 1	4	4	5
User 2	5	4	5
User 3	5	5	4
User 4	3	5	4
User 5	5	4	4
User 6	5	3	3
User 7	5	3	2
User 8	4	5	5
User 9	5	2	3
User 10	5	4	3
User 11	5	3	5
User 12	4	3	4
User 13	5	5	5
User 14	5	5	5
User 15	4	3	2
User 16	4	4	4
User 17	5	5	5
User 18	4	5	3
User 19	3	5	4
User 20	5	5	5
User 21	4	3	4
User 22	3	4	2
User 23	5	5	5
User 24	4	3	4
User 25	4	5	5
User 26	5	4	5
User 27	4	4	4
User 28	5	3	5
User 29	5	5	5
User 30	5	2	4
User 31	4	2	5
User 32	4	3	3
User 33	5	5	4
User 34	5	2	5
User 35	5	4	5
User 36	5	4	5
User 37	4	3	4
User 38	4	3	4
User 39	5	5	5
User 40	3	3	3

Question 3: The interaction mode is efficient.

	Controller -based	Hand Gesture	Mixed
User 1	5	3	4
User 2	5	2	3
User 3	3	4	2
User 4	5	3	3
User 5	5	4	3
User 6	4	5	4
User 7	4	4	4
User 8	5	4	3
User 9	5	2	4
User 10	5	3	3
User 11	5	3	3
User 12	4	4	4
User 13	5	3	2
User 14	5	5	5
User 15	3	2	1
User 16	3	5	4
User 17	4	4	3
User 18	5	2	3
User 19	3	3	5
User 20	3	4	3
User 21	4	4	5
User 22	4	4	3
User 23	5	4	4
User 24	3	2	3
User 25	5	4	4
User 26	4	3	5
User 27	4	4	2
User 28	5	3	5
User 29	5	2	4
User 30	5	1	3
User 31	4	3	5
User 32	4	3	4
User 33	5	4	3
User 34	5	1	5
User 35	5	4	4
User 36	5	4	4
User 37	4	3	4
User 38	3	4	4
User 39	4	3	4
User 40	3	2	3

Question 4: I found it easy to select an object using the interaction mode.

	Controller -based	Hand Gesture	Mixed
User 1	4	2	4
User 2	5	2	4
User 3	5	4	3
User 4	5	3	4
User 5	5	4	4
User 6	5	5	5
User 7	5	3	2
User 8	5	4	3
User 9	5	2	3
User 10	5	4	4
User 11	5	4	4
User 12	5	3	4
User 13	5	3	4
User 14	5	5	5
User 15	4	3	1
User 16	4	4	4
User 17	5	3	4
User 18	5	1	2
User 19	3	5	5
User 20	3	3	3
User 21	5	3	5
User 22	5	4	4
User 23	4	5	5
User 24	3	3	4
User 25	5	5	5
User 26	5	4	4
User 27	5	5	3
User 28	3	4	4
User 29	5	3	4
User 30	5	1	3
User 31	5	3	5
User 32	3	4	3
User 33	5	3	5
User 34	5	2	5
User 35	5	4	4
User 36	5	3	4
User 37	4	3	5
User 38	4	4	4
User 39	4	4	5
User 40	3	4	3

Question 5: I found it easy to move an object using the interaction style.

	Controller -based	Hand Gesture	Mixed
User 1	4	4	4
User 2	5	3	4
User 3	4	4	3
User 4	5	3	4
User 5	5	4	3
User 6	4	3	3
User 7	5	3	2
User 8	3	4	3
User 9	5	2	3
User 10	4	4	3
User 11	5	2	3
User 12	4	2	3
User 13	4	4	5
User 14	5	5	5
User 15	4	2	1
User 16	4	5	4
User 17	3	4	3
User 18	5	2	3
User 19	4	5	5
User 20	3	3	3
User 21	4	5	5
User 22	5	4	4
User 23	4	3	2
User 24	4	3	4
User 25	5	4	5
User 26	5	4	4
User 27	3	3	1
User 28	5	5	4
User 29	5	4	5
User 30	5	1	4
User 31	5	3	5
User 32	3	4	3
User 33	5	4	3
User 34	5	3	5
User 35	4	3	4
User 36	5	3	5
User 37	4	2	4
User 38	4	3	5
User 39	5	4	5
User 40	3	3	3

Question 6: I found it easy to rotate an object using the interaction style.

	Controller -based	Hand Gesture	Mixed
User 1	3	3	4
User 2	5	1	4
User 3	5	4	4
User 4	5	2	3
User 5	4	4	4
User 6	5	3	3
User 7	4	4	3
User 8	4	5	3
User 9	5	3	4
User 10	5	4	4
User 11	5	4	4
User 12	3	2	2
User 13	3	4	5
User 14	4	5	5
User 15	4	2	1
User 16	3	4	4
User 17	3	5	4
User 18	5	1	3
User 19	4	5	5
User 20	5	3	3
User 21	3	5	5
User 22	4	5	4
User 23	4	5	4
User 24	3	4	4
User 25	3	5	5
User 26	5	4	5
User 27	5	5	2
User 28	5	2	4
User 29	5	2	4
User 30	4	1	3
User 31	4	2	5
User 32	3	4	4
User 33	5	4	3
User 34	4	1	5
User 35	5	3	3
User 36	4	4	4
User 37	3	2	3
User 38	3	5	4
User 39	5	4	5
User 40	3	3	3

Question 7: I found it easy to dock an object using the interaction style.

	Controller -based	Hand Gesture	Mixed
User 1	3	2	3
User 2	4	2	3
User 3	4	5	2
User 4	3	4	4
User 5	5	3	3
User 6	5	5	4
User 7	5	4	3
User 8	4	4	2
User 9	5	4	3
User 10	5	4	4
User 11	5	4	4
User 12	4	3	3
User 13	5	3	3
User 14	5	4	4
User 15	3	1	1
User 16	3	4	4
User 17	4	3	3
User 18	5	1	4
User 19	3	4	4
User 20	4	4	4
User 21	3	3	3
User 22	5	4	4
User 23	4	3	2
User 24	3	2	3
User 25	4	5	5
User 26	4	5	4
User 27	3	3	3
User 28	5	3	4
User 29	5	5	5
User 30	4	1	3
User 31	5	3	5
User 32	3	4	4
User 33	4	3	2
User 34	4	1	5
User 35	4	4	4
User 36	5	4	4
User 37	4	1	4
User 38	3	3	4
User 39	5	4	5
User 40	3	3	3

Question 8: I would like to use the interaction style frequently.

	Controller -based	Hand Gesture	Mixed
User 1	5	2	4
User 2	5	1	3
User 3	4	4	2
User 4	5	3	3
User 5	4	2	1
User 6	4	5	3
User 7	5	3	2
User 8	3	5	1
User 9	5	4	2
User 10	5	4	2
User 11	5	4	2
User 12	4	2	2
User 13	4	3	4
User 14	5	5	4
User 15	3	1	1
User 16	3	4	4
User 17	4	5	3
User 18	5	1	3
User 19	4	5	5
User 20	4	4	4
User 21	3	4	5
User 22	4	5	3
User 23	4	4	2
User 24	3	2	5
User 25	3	5	5
User 26	5	4	4
User 27	4	4	2
User 28	5	3	4
User 29	5	2	5
User 30	5	1	3
User 31	4	2	5
User 32	3	4	2
User 33	5	4	3
User 34	5	1	5
User 35	5	4	5
User 36	5	3	4
User 37	2	2	2
User 38	4	3	5
User 39	5	4	5
User 40	3	3	3

Question 9: I felt very confident using the interaction style.

	Controller-based	Hand Gesture	Mixed
User 1	5	4	4
User 2	5	3	4
User 3	4	5	3
User 4	4	4	4
User 5	5	4	3
User 6	4	5	3
User 7	5	3	2
User 8	5	5	5
User 9	5	4	2
User 10	5	4	3
User 11	5	3	5
User 12	5	3	4
User 13	5	3	3
User 14	5	5	4
User 15	5	5	5
User 16	4	5	5
User 17	5	4	3
User 18	5	1	2
User 19	3	4	4
User 20	4	4	4
User 21	4	4	5
User 22	3	3	3
User 23	4	4	4
User 24	3	2	4
User 25	4	5	5
User 26	4	5	4
User 27	5	5	3
User 28	5	3	4
User 29	5	2	4
User 30	5	1	4
User 31	5	4	5
User 32	3	4	3
User 33	5	4	2
User 34	5	1	5
User 35	5	5	5
User 36	5	5	5
User 37	3	2	3
User 38	4	3	3
User 39	5	4	5
User 40	1	2	2

Question 10: The interaction style was effective in helping me complete the tasks.

	Controller-based	Hand Gesture	Mixed
User 1	4	2	4
User 2	5	3	3
User 3	4	5	3
User 4	5	3	3
User 5	5	4	1
User 6	4	5	3
User 7	5	4	2
User 8	5	5	1
User 9	4	3	2
User 10	5	5	4
User 11	5	4	5
User 12	4	3	3
User 13	5	4	4
User 14	5	5	5
User 15	3	1	1
User 16	4	4	4
User 17	4	4	3
User 18	5	1	3
User 19	4	5	5
User 20	4	4	4
User 21	4	4	5
User 22	4	5	3
User 23	4	4	3
User 24	3	2	4
User 25	3	5	5
User 26	5	4	5
User 27	4	4	4
User 28	5	3	5
User 29	5	3	4
User 30	5	1	4
User 31	4	3	5
User 32	4	4	4
User 33	5	4	2
User 34	5	1	5
User 35	5	5	5
User 36	5	4	4
User 37	3	2	4
User 38	4	3	4
User 39	5	4	5
User 40	3	4	3

Question 11: It was enjoyable to use this interaction.

	Controller-based	Hand Gesture	Mixed
User 1	4	4	5
User 2	5	4	4
User 3	4	5	2
User 4	5	2	3
User 5	5	5	4
User 6	5	5	4
User 7	5	5	5
User 8	4	5	1
User 9	5	5	3
User 10	5	5	4
User 11	5	5	5
User 12	4	4	4
User 13	5	5	5
User 14	5	5	5
User 15	3	1	1
User 16	5	5	5
User 17	4	5	3
User 18	5	1	3
User 19	5	5	5
User 20	4	4	4
User 21	5	5	5
User 22	4	5	3
User 23	4	5	5
User 24	3	4	5
User 25	3	5	5
User 26	4	3	5
User 27	5	5	2
User 28	5	4	5
User 29	5	3	5
User 30	5	2	4
User 31	4	4	5
User 32	3	5	4
User 33	5	5	5
User 34	5	1	5
User 35	5	5	5
User 36	5	5	5
User 37	3	3	4
User 38	4	3	5
User 39	5	4	5
User 40	3	3	4

Question 12: For the tasks I was asked to do, I prefer this interaction style the most.

User 1	Controller-based
User 2	Controller-based
User 3	Hand Gesture
User 4	Controller-based
User 5	Controller-based
User 6	Hand Gesture
User 7	Controller-based
User 8	Controller-based
User 9	Controller-based
User 10	Controller-based
User 11	Controller-based
User 12	Controller-based
User 13	Controller-based
User 14	Mixed Interaction
User 15	Controller-based
User 16	Mixed Interaction
User 17	Controller-based
User 18	Controller-based
User 19	Mixed Interaction
User 20	Controller-based
User 21	Mixed Interaction
User 22	Controller-based
User 23	Mixed Interaction
User 24	Mixed Interaction
User 25	Mixed Interaction
User 26	Mixed Interaction
User 27	Hand Gesture
User 28	Controller-based
User 29	Controller-based
User 30	Controller-based
User 31	Mixed Interaction
User 32	Hand Gesture
User 33	Controller-based
User 34	Mixed Interaction
User 35	Controller-based
User 36	Controller-based
User 37	Mixed Interaction
User 38	Mixed Interaction
User 39	Mixed Interaction
User 40	Mixed Interaction

Question 13: Overall, I prefer this interaction style the most.

User 1	Controller-based
User 2	Controller-based
User 3	Hand Gesture
User 4	Controller-based
User 5	Controller-based
User 6	Controller-based
User 7	Controller-based
User 8	Hand Gesture
User 9	Leap Motion
User 10	Controller-based
User 11	Controller-based
User 12	Controller-based
User 13	Mixed Interaction
User 14	Mixed Interaction
User 15	Controller-based
User 16	Mixed Interaction
User 17	Hand Gesture
User 18	Controller-based
User 19	Mixed Interaction
User 20	Controller-based
User 21	Mixed Interaction
User 22	Hand Gesture
User 23	Hand Gesture
User 24	Mixed Interaction
User 25	Controller-based
User 26	Mixed Interaction
User 27	Controller-based
User 28	Controller-based
User 29	Controller-based
User 30	Controller-based
User 31	Mixed Interaction
User 32	Hand Gesture
User 33	Controller-based
User 34	Mixed Interaction
User 35	Controller-based
User 36	Controller-based
User 37	Mixed Interaction
User 38	Mixed Interaction
User 39	Mixed Interaction
User 40	Mixed Interaction

Question 14: How mentally demanding was the task?

	Controller-based	**Hand Gesture**	**Mixed**
User 1	16	18	17
User 2	6	13	8
User 3	1	1	4
User 4	7	7	7
User 5	1	5	5
User 6	4	10	8
User 7	7	13	17
User 8	10	10	10
User 9	4	13	9
User 10	6	8	12
User 11	5	15	11
User 12	12	16	14
User 13	6	10	5
User 14	3	3	13
User 15	5	5	5
User 16	9	11	12
User 17	6	4	9
User 18	11	20	7
User 19	11	8	9
User 20	11	11	11
User 21	11	11	8
User 22	11	17	17
User 23	8	13	10
User 24	13	18	7
User 25	3	5	5
User 26	5	8	3
User 27	11	11	15
User 28	5	14	14
User 29	11	11	11
User 30	2	17	11
User 31	13	17	9
User 32	10	10	10
User 33	5	19	17
User 34	8	14	6
User 35	3	8	14
User 36	1	9	6
User 37	10	18	18
User 38	11	7	13
User 39	5	5	5
User 40	11	12	6

Question 15: How physically demanding was the task?

	Controller-based	Hand Gesture	Mixed
User 1	12	17	14
User 2	7	10	10
User 3	1	1	2
User 4	10	3	7
User 5	1	1	1
User 6	1	1	1
User 7	2	2	2
User 8	10	10	10
User 9	4	15	15
User 10	5	5	8
User 11	2	15	14
User 12	7	12	10
User 13	5	8	8
User 14	2	2	6
User 15	15	10	15
User 16	13	13	15
User 17	4	6	9
User 18	2	20	9
User 19	3	2	3
User 20	11	11	11
User 21	13	11	11
User 22	11	14	14
User 23	8	5	12
User 24	9	13	8
User 25	1	1	1
User 26	7	8	6
User 27	11	11	12
User 28	7	15	13
User 29	1	4	11
User 30	3	20	13
User 31	11	17	11
User 32	14	8	11
User 33	4	11	15
User 34	3	3	3
User 35	2	2	2
User 36	10	15	11
User 37	8	14	8
User 38	14	10	12
User 39	3	6	3
User 40	11	13	9

Question 16: How successful were you in accomplishing what you were asked to do?

	Controller-based	Hand Gesture	Mixed
User 1	3	4	3
User 2	3	14	9
User 3	4	2	16
User 4	1	10	6
User 5	1	5	10
User 6	5	3	7
User 7	6	6	6
User 8	4	4	17
User 9	1	13	7
User 10	3	4	6
User 11	10	13	10
User 12	4	10	7
User 13	4	8	8
User 14	4	5	8
User 15	5	13	17
User 16	7	7	7
User 17	4	4	7
User 18	2	20	9
User 19	14	9	9
User 20	11	11	11
User 21	8	7	5
User 22	13	15	15
User 23	14	14	5
User 24	11	13	4
User 25	4	3	2
User 26	1	2	1
User 27	4	5	12
User 28	12	12	7
User 29	5	11	3
User 30	5	15	9
User 31	5	11	1
User 32	5	3	8
User 33	11	19	21
User 34	10	14	5
User 35	14	9	7
User 36	1	2	1
User 37	13	9	5
User 38	13	10	16
User 39	4	9	3
User 40	11	11	10

Question 17: How hard did you have to work to accomplish your level of performance?

	Controller -based	Hand Gesture	Mixed
User 1	12	13	12
User 2	6	14	13
User 3	6	4	14
User 4	5	10	8
User 5	1	1	20
User 6	3	3	5
User 7	11	14	17
User 8	13	14	20
User 9	4	15	12
User 10	6	7	8
User 11	6	15	10
User 12	10	19	16
User 13	2	9	6
User 14	2	3	5
User 15	8	15	16
User 16	12	12	14
User 17	4	6	7
User 18	15	20	11
User 19	15	7	11
User 20	11	11	11
User 21	11	11	11
User 22	11	17	17
User 23	11	11	13
User 24	8	15	7
User 25	6	12	11
User 26	3	4	2
User 27	13	14	18
User 28	10	13	6
User 29	11	21	11
User 30	4	20	12
User 31	11	15	5
User 32	7	12	15
User 33	6	17	21
User 34	11	13	7
User 35	10	14	19
User 36	1	11	7
User 37	11	16	9
User 38	12	9	13
User 39	9	14	2
User 40	16	17	13

Question 18: How insecure, discourage, irritated, stressed, and annoyed were you?

	Controller -based	Hand Gesture	Mixed
User 1	4	5	4
User 2	4	14	10
User 3	1	1	6
User 4	1	3	2
User 5	1	1	20
User 6	2	1	1
User 7	1	1	1
User 8	3	6	18
User 9	1	8	5
User 10	3	7	8
User 11	1	1	1
User 12	10	17	15
User 13	2	7	4
User 14	1	1	4
User 15	9	16	19
User 16	13	14	15
User 17	4	4	6
User 18	2	16	7
User 19	15	8	11
User 20	11	11	11
User 21	1	1	1
User 22	4	6	6
User 23	9	8	14
User 24	10	14	5
User 25	4	4	4
User 26	2	4	2
User 27	9	9	19
User 28	12	18	3
User 29	1	18	11
User 30	3	21	15
User 31	6	11	1
User 32	2	2	4
User 33	4	15	18
User 34	3	15	1
User 35	1	1	1
User 36	1	11	5
User 37	13	16	9
User 38	13	15	18
User 39	7	14	2
User 40	11	11	10

Appendix 11: Shapiro-Walk Test

Controller - Puzzle 1	
W-stat	0.75686777
p-value	0.000001
alpha	0.05
normal	no

Controller - Puzzle 2	
W-stat	0.86461026
p-value	0.00024727
alpha	0.05
normal	no

Controller - Puzzle 3	
W-stat	0.75896241
p-value	0.000001
alpha	0.05
normal	no

Leap Motion - Puzzle 1	
W-stat	0.9061741
p-value	0.00333239
alpha	0.05
normal	no

Leap Motion - Puzzle 2	
W-stat	0.896225
p-value	0.00172275
alpha	0.05
normal	no

Leap Motion - Puzzle 3	
W-stat	0.88657839
p-value	0.00093011
alpha	0.05
normal	no

Mixed - Puzzle 1	
W-stat	0.877784
p-value	0.0005404
alpha	0.05
normal	no

Mixed - Puzzle 2	
W-stat	0.83402254
p-value	0.00005
alpha	0.05
normal	no

Mixed - Puzzle 3	
W-stat	0.81178281
p-value	0.00001
alpha	0.05
normal	no

Appendix 12: Talk-aloud Verbal Protocol

Participant ID	Comments
1	"Yes, perfect. I was able to pinch."
2	
3	"Controller is better in some movements, but some are better with my own hands" "Leap Motion is much easier than controller"
4	"I can use my hands"
5	"I feel like the, like getting use to controller to do the right motion."
6	"wow, the Leap motion is so cool. I like the ease of it…it's a lot easier than the controller, I have a VR headset for years" "The mixed is so good and new, that's weird to see a controller and hand"
7	"oh, the controller is chippy" "The Leap Motion is pretty easy" "I found that a bit easier to have controller in my dominant hand"
8	"It's kinda weird of not having anything that you can physically touching(Leap Motion)"
9	"The Leap Motion is fun"
10	"I like playing with the tracking of Leap motion"
11	"I like using both of them"
12	"I need to do it slower."
13	"Use controller to grasp, use Leap Motion to rotate is quicker."
	"Move object over to another hand with your own hand is easier with leap"
14	"Easy to slide with right hand with Leap Motion, but twisting is hard, I'm struggling." "Place object with controller." "For the right hand you have to click it, but left hand you don't, so that's confusing."
15	"I need to use two hands" "Leap Motion is getting my fingers mixed up"
16	
17	"With the controller, it always feel heavier." "Vive is definitely more intuitive"
18	
19	"I use fingers for the first puzzle in mixed interaction"
	"I find it easier to use my own hands"
20	"The leap is easier in puzzle 1, but harder in puzzle 3"
21	
22	"Actually, that fixed the previous mistakes in mixed interaction"
23	"Come back with thoughts in mixed interaction, I can see the potential in shooting games" "The controller is easy"

24	"I also placed the controller on the table. Leap motion is smooth, but a little exhausted" "Mixed interaction is very intuitive"
25	"It's easy to use mixed interaction"
26	"Leap motion is so realistic"
27	"Need practice in mixed interaction, it's interesting"
28	"Leap motion is making me mad, it's hard"
29	"I'm hot, can I sit down?"
30	"The controller is so cool, but I'm tired" "Leap Motion is so cool, and I quickly did it."
31	"Feel like using both"
32	"I like the haptic of controller"
33	
34	"It's hard to slide with a controller"
35	"The experience is amazing…oh my gosh…" "That's crazy…(Leap Mtoion)" "It's easier to pickup by my right hand with Leap Motion"
36	"I'm struggling with Leap" "Able to decide which interaction style to use in the three puzzles."
37	"For example, Leap motion to slide, mixed for tower, controller for interlocking puzzle."
38	"Leap is hard"
39	"It feels so weird"
40	"Both controller and leap are hard to control"

Appendix 13: Participation Interview Questions

Q1: Can you describe how you found the interaction task?

Q2: How demanding, both physically and mentally, did you find the task?

Q3: How successful do you think you were in conducting the task?

Q4: How did the mixed interaction mode contribute to your success?

Q5: What will be the difference if you were given a set of controllers or using only leap motion?

Q6: What sort of use cases can you see as benefiting from this type of mixed interaction?

Appendix 14: Interview Transcript with Codes

Q1: Can you describe how you found the interaction task?

Interview Transcript	Codes
User #01 It was very unique experience to have. And interacting with the objects made you feel like you more immersed in the cockpit, I mean it's already immersive sitting in the cockpit and actually touching and moving the controls. The right hand, the ghost hand and there was very connected, it was very one to one with my movements of my hand. Of course, the knob was difficult to get the technique right to adjust but for the pushing the controls backwards and forwards and flicking the switches that was easy. I find them more of a swift pension twist straight away to activate if you holding it, it kind of doesn't register that interaction with the knob itself.	Unique experience Immersive and felt connected Difficult to turn the knob Easy to push the switches and buttons
User #02 I found them fairly simple and straight forward most of the stuff like the knobs and flicking the switch was I just kind of knew how to do based on real world experiences, something I found with the knobs that are to pinch quite hard. Normally, in real life I have my fingers a little bit apart I guess but in Leap motion you can have them really close and pinch it which is something I found quite odd I guess.	Straightforward, close to real world experiences Hard to pinch the knobs
User #03 The interactions, they work surprisingly well to be honest and I especially for it just tracking my hand and being able to interact with the environment that so much like it's a strange experience at first but it almost is like second nature in a way it feels and like I'm actually there it's super cool everything works really well.	Interaction is surprisingly well Strange experience but feels natural Satisfied with the work
User #04 They were very simple to do, it was quite fun actually being able to interact with like being able to use my entire hand also like having the other hand ready on the joystick to actually move it around. There was some difficulties like previously mentioned about the turning the dial but everything else felt really smooth and it was really impressive to see it actually just know my hand was there but immediately work with it.	Tasks are simple Fun experience Turning the knob is difficult Smooth Impressive experience
User #05 They are straightforward and simple and maybe for the dial turning it was more glam because I wasn't sure which dial to turn it first, but then afterward I asked you was actually saying turn any dial. So that would maybe first you just say turn any dial that would make it faster and more efficient. The horizon calibration test was a little strange, because I wasn't sure how exactly because there was like a bend into lumps so will not sure where to place the land on the horizon, the rest of the tests were very simple and straight forward and I enjoy it.	Interaction tasks are straightforward and simple Very simple and straightforward

User #06 It's like pretty much the same as all VR stuff that I tried, it's the whole depth perception thing, you know in VR like there's always like the lack of information like you can visually see it but there's no feedback so you are always blindly pushed into something, but I mean the whole leap motion that's pretty cool, it tracks my fingers pretty well, it's like using lidar or something. User #07 So with the interaction tasks I found that using the leap motion was a bit harder since it was like disappearing all the time and reappearing I guess is because of the leap sensors but also like when you do another tasks it feels like when you, for instance go press a button or move the lever doesn't like feel like you're grabbing onto it like you just pushing through the controller I felt like I was grabbing onto something or moving something when I have it cause I have like something on my hand I felt a lot easier to use. User #08 The interaction in general, it was easy it was visually appealing, so you can visually detect and understand things when you tell that is knob the lever the button is easy to see it and yes that's a button then press it and they were responsive enough if I try to press the button it reaction was OK. The leap interaction is very very very very good I could see and map the movement of my hand with the movement of the representation in the game so it was easy to use, it was not hard to try to do things and try to find how to press things or to move things The response, maybe it needs a little bit of more visual flair, it suppose like visual indication of when you're interacting with your right hand with the controller ie was perfect because the moment you have the controller it has a little of what you were doing and with the leap, it needs more hover effect, with something that indicates that you are actually interacting with something because there is no like haptic feedback for the hands so you only have to rely on visuals and sometimes just seeing the thing moving or especially the buttons like are you pressing it or not, so a more visual distinct visual representation would be better because you don't have the physicality to know that you're doing something.	Enjoy the experience No feedback can be unsure Enjoy using Leap Motion Leap Motion was a bit harder Feel easier to use a controller Easy interaction Visually appealing Knob, lever, and button are easy Responsive interaction design Leap motion is very good Easy to use Visual cues needed

Q2: How demanding, both physically and mentally, did you find the task?

Interview Transcript	Codes
User #01 Not demanding at all. It's very smooth and very easy. Physically, of course there's nothing heavy about moving your own arm so it was very natural. Mentally, that looks like there's a lot of controls and of course I don't know what most of them do apart from just a general idea of a flight cockpit, so yeah once you have a good look around and	Very smooth and easy Very natural experience

you've been sitting in the cockpit for a little bit you're like OK here's the bottom control and is some buttons over here and what I quite like is clearly marked AP, so yeah pretty easy. User #02 I don't personally find it demanding at all, i guess mainly because i'm only using one hand at a time if i was to use both i think it would be more demanding. But in terms of flicking couple switches with my fingers. It was quite intuitive as well, being able to use fingers to press buttons. User #03 Not actually that demanding, considering I'm sitting at a chair so it's quite leisurely compared to a lot of like other VR activities. Most of it was fairly easy cause it was just pushing buttons it's probably the most difficult was that the stick is my hand was a bit shaky because it's in the mid air, so I thought maybe I could put it on my leg maybe it would have been more stable but most of it was fairly leisurely. User #04 Didn't feel it stressful, the instructions were clear and everything was quick and easy to do. User #05 I find the task very simple; I feel anybody could do that with like a reasonable understanding of VR so you don't feel strange about having two different tools at one time. I do not feel different it feels like as if I'm just using a keyboard and a mouse because that feels, because they are totally different but feels very intuitive to a person who uses a computer all the time, that's kind of how I see it. User #06 I found it yeah it's almost easy, it's just like again on the previous one I just had to think about the how much force or how far do I extend my arm out and all that stuff because obviously there's a lag time between the lidar feedback and the hand haptic feedback. So it's not too taxing for my brain but yeah I feel no pressure. User #07 It was quite simple like I didn't need to use any mental capacity to do any of the tasks. User #08 Not much, I'm accustomed to both interactions, so maybe I am a little trained. But in general, It's easy because it was responsive that there was no delay in the movements the connection was good, there was enough feedback to know what you were doing and the interaction was simple enough like only touch interactions and even the lever was not that much of an interaction to hold that normally is the ones that	Buttons are pretty easy Intuitive interaction Fairly easy Mid-air with the controller is difficult Quick and easy Tasks are very simple Not strange to have different tools with VR experience Totally different but very intuitive Easy No pressure Quite simple Easy and responsive No delay, the connection was good Interaction was simple

are more like normally, you try to naturally do that and it responded to it so it is easy.	Naturally do that, it responded to it Easy

Q3: How successful do you think you were in conducting the task?

Interview Transcript	Codes
User #01 I think probably 80% pretty easy, yeah I think that's levelling the plane off I didn't look around so the horizontal line wasn't actually true horizontal when I set to autopilot, but the fact that I guess I didn't really know the controls but you know following tasks is pretty one to one, the directions are very straight forward so it was good. User #02 I think that goes pretty successful once I got the hang of it. I think once it took me let's say like a minute to get used to the leap motion cause it was quite weird using actual fingers cause I'm so used to buttons like physical buttons on the controller but once I got the hang of it, it was pretty straight forward like once I was doing involves the switches and stuff. User #03 I felt like I was successful thinking back i'd say like 80%, a couple of things maybe i was a bit too fast and the dials i think yeah it took me a bit to find the actual like correct pinch together but once i got it was it was easy. User #04 I feel like I've got that pretty quickly aside from turning the dials port but yeah everything felt snapping smooth, and it was really easy quickly do everything once you told me which part was. User #05 I think I did very well. User #06 I think I did OK. I ticked all the boxes right and very confident. User #07 Pretty successful, I mean it did take me a few seconds to find what button you are talking about but like pressing levers and turn knobs are pretty easy. User #08 I suppose it was quite successful, I did not kill myself. I'm confident in general.	Pretty easy Straightforward and good Pretty successful Quite weird Straightforward once involves switches and stuff Successful Easy Aside from turning dials Smooth, easy, quick Confident Very confident Pretty successful Pressing levers and turn knobs are pretty easy Quite successful

Q4: How did the mixed interaction mode contribute to your success?

Interview Transcript	Codes
User #01 I think that it was extremely useful like just having the ability to see your hand and exactly where it goes in the 3D space. It's different than holding the controller like the controller you have the hand floating in mid-air and is a very disconnected feeling and of course it still works because you can see where it's placed in 3D space as well, but it's kind of looks very robotic whereas the leap motion was a very good representation of the actual hand so you know when you go down to reach something it was very…It's there. It's not a blob floating in space and when you pull the controllers to grab something, it's unnatural whereas when you just pick a knob and twist it and flip switches it's very neat.	Extremely useful Controller you have the hand floating in mid-air and is a very disconnected feeling Prefer Leap motion
User #02 I think it was contributed because being able to have controller in one hand and able to have the other hand free, was I think much easier than using two controllers for me personally like having like rather trying to focus on two physical objects in your hand once having one hand like freely move, the other hand being able to hold controller and do stuff as well. I think if I was both free hands I will have a lot more troubles.	New interaction compared to traditional modes
User #03 It definitely just added an entirely new way of how it felt. I think it was super I think it definitely did as it was super interesting like my hand my real hand is moving like in real time in the space and I felt like I could actually reach out and touch them turn the knobs whereas something like the vive controller it sometimes I've played with those in the past so it gets like real finicky trying to pick things up or my hand gets tired whereas this didn't feel like any fatigue was on my hand at all so it was it is a lot easier to actually use my real hand.	New way New experience Interesting to see real hands in VR Hands get tired when using controller
User #04 It was definitely quick to tell that I could know the ease of having that free hand to do whatever I needed with my fingers and having the other hand just ready to move probably. It felt right it felt proper it felt correct like yeah like being able to freely do anything with my other hand while the other while my left hand was meant to be on the joystick ready to move it around and felt really naturally basically.	Ease of mixed interaction Feel right, proper, correct and natural
User #05 The thing is the tasks were independent that wasn't requiring me to use both interfaces at the same time which is what I feel made it much easier because for example if I had to use the both mixed interface to do one task that would make it much much more difficult for an average person because they wouldn't know how to do if they are new to VR but because it was independent and because he said this is one task will use the controller and this another task used the scan(leap motion), that was much easier than I thought.	Maybe mixed interaction can be hard for people who are new to VR

User #06 So the mixed one like it was weird having the hand like free, it was very weird but then like but the stick was like down like a comfort blanket for me, you know I'm used to having controls and stuff but it was the this whole thing was new so I think I like the mixed control concept but if the whole thing becomes like both hands with a Leap Motion thing I think it's going to be like weird.	Mixed interaction brings a weird experience Prefer mixed interaction, it is a new concept
User #07 It's a bit weird like having one controller and the one without, that's quite of an odd feeling of just being able to like grab something with your hand but like have like nothing bare so you're just kind of acting like you grabbing something.	Weird experience on mixed interaction
User #08 It's always good to have something in your hand that they haptic feedback is useful either because you're expecting like the virtual simulation an it's a little offsetting to like try to press something or to pull something and feel nothing so at least the physical feedback of the controller helps you and if you are a little more into this type of interaction or you're like a gamer or something like that having the feeling of the controller on trying to map movement to the controller like the trigger or something like that that feels very natural and easy to do and we have been doing probably quite a while in your life so it's something that you expect when you're trying to do these kinds of interaction, so having the controller this is interesting having the hand and not feeling anything, it can be a little upsetting but the mixed interaction is quite good and the model of the hand was very interesting too because it was not obtrusive of the of the visualisation sometimes you have like a skeleton like something you have like a real hand or a transparent like a skeleton one and that looks cool but sometimes it's distracting because you don't know if you're pressing, you're trying to watch if I'm doing it or not because you don't have to the haptic feedback, it could be a little distracting so the handle was interesting that the thing I like it because it let you be more confident of where are you putting the handle whether affecting with the hand so again like compliment to the lack of haptic feedback that all of those visual cues calculated are very very good.	Feels natural and easy with the controller Mixed interaction is quite good with the transparent hand Distracting when there is no haptic feedback the handle was interesting to cover the lack of hand feedback

Q5: What will be the difference if you were given a set of controllers or using only leap motion?

Interview Transcript	Codes
User #01 I think not having that immersion in completing the tasks I assumed because I didn't use a controller to do exactly the same task before is I don't really have a connection between…knowing if I will be more successful with turning that knobs say for example, where is your hand is so accurate and I think that I would rather the leap motion any day then the Vive controller just from it has issues if you hide your hand, your fingers all start to kill in 3D space as a little bit of a disconnection there but it was still better than having an open hand grip from live controller floating around in front of you and having that modelled all the way down instead of chopped off (hand). I think that it would be different if I could performance from my end not too sure about because a lot of it comes down to the how well the hand would be programmed for individual switches like for example if I was using the Vive controller and I went to go and push a button and it pushes the one above it or I've had it where you tried pinch something will grab it at control and it doesn't quite grab at the same either so I think that if I didn't have that problem with grabbing and twisting the knob, I'd say that I would perform better with the leap motion than the vive controller, I feel comfortable with the mixed controller.	Extend hand model in controller Feel comfortable with mixed interaction
User #02 So if I was going to use two controllers, I will find it much more difficult to do the tasks, because of I guess with controllers it's more so like the struggle is also finding where the buttons are to control and all that as well. And something like I like how this is like I have particular the left controller was something physical in the game but you pushed you know like aligning the skyline, whereas the left is lack of buttons, and I both were free or even kind of weird grasping onto that skyline thing without having to actually hold some physical in my hand they've got like a it was felt fairly like real life simulation kind of like you know like in real life the whole like a little joystick and clicking stuff your fingers.	Hard to find the buttons with a controller
User #03 What I said before is I played a lot of games using the vive controllers a lot of them where they would have you picked things up but you would have to hold the bottom grip buttons but then they would also use the grip buttons for holding on to things I think as it would be like the grip button does like that and in the trigger does that yeah sorry the index finger and then usually the other three the grip and I would notice a lot playing these games that my hands get really tired and I would have to like take a break or it would feel like they're strain on my hand where is if it was Leap Motion it just felt like supernatural and really like easy head compared to the controllers. I could immediately think of is if I had like an actual controller is they could be like some sort of haptic feedback with vibrations which may go like a bit further and selling the experience but I think the trade-off	Hands get tired with a controller Leap Motion brings natural experience compared to controller

of actually having like my real hands was like worth it and good so I think that's how I differ the experiences. Touching all the small buttons are way easier like could be way more successful doing that whereas the controller I feel like it's very refined and you have to get it like right on.	Using Leap Motion to touch the buttons are easy
User #04	
I can definitely tell about grabbing onto the joystick would have been a bit more difficult and probably less precise if I had free movement in my left hand and definitely I could see it would feel a lot less natural like I miss the controller if it was on my right hand like pushing the frost forward I'd probably have the controller sideways to make it feel right, but it feels more responsive to have that free hand and another controller. Everything else it just definitely feels a lot more natural just being able to point and press my finger against than smashing the entire controller into it.	Use of controller on the sidestick is appropriate It feels right and responsive with mixed interaction
User #05	
I feel the leap motion was significant enough to do simple tasks, but I do feel more comfortable with the controller because it's more tactile and I can feel me actually squeezing, once its trigger, it just triggered. For the leap motion you don't know if it's triggered or not so like even if I put my fingers together I don't know if I'm holding a knob yet, unless is like a very significant visual indicator that it's been triggered, because the visually that it wasn't there but perhaps that was more visually significant, the leap motion would be better because I feel more intuitive just to your finger to push then trying to hold a controller user fist almost.	Leap motion can do simple task, as it does not have feedback Unsure about Leap motion Visual indicator
User #06	
So like I said in the previous one there's always like the lack of information in terms of like the sense of touch doesn't serve like the pressure in your hands so having the controllers in my hand so be kind of comforting in a sense coz that you're actually grasping it something but in some certain tasks when like pushing buttons it doesn't make sense and like it kind of ruins the immersion, feel like just like directly aiming the controller at something and then pushing a button to activate or something but if you have the leap motion it's more immersive but then there's also the drawback of like not feeling anything like you're always just trying to visually depend on like visual cues and stuff so I guess that's that would be the main difference for me. For example, I mean technically I I think I would perform better with controllers because that's what I'm used to but then like if I reckon if I'm exposed enough to leap motion, the whole thing i would do ok with it. So, I like the mixed.	Controller gives a sense of touch is comforting Visual cues
User #07	
Yeah like if I were to just to use the leap motion, I feel like my hands are quite light like I'm not like you know how you grab an object and you can like feel how heavy it is, with the leap motion when you need	

like grabbing something it feels like everything is just weight nothing. It's like if I had no touch or anything it's like trying to pretend that you're turning the knob or something, but you got the visual, but it's kinda hard with the realism like interactive things. If I was given the controllers, I don't know why but it feels more realistic in grabbing something. With the controller you feel like you have something in your hand and it's like weighted, and if you like turn a button, it feels like you actually like rotating something. It's just a feeling of having weight in your hand. I don't know… User #08 With only controllers maybe I would feel a little more in control but I feel more comfortable with the mixed interaction, with only leap hands maybe the thing that could happen is that after a while I will be very careful of always trying to see my hand, with the controller I can like put my hand in my lab and you still know that it is there. With only the leap, I feel I have to always be like this because if not I lose completely the hands that would be very very tiring so at least having one hand I could have like here with no problem and the other just swapping them in and out it feels a bit more comfortable maybe two hands like this could be quite tiring a little like a little too much load to your processing like your cognitive process of trying to do what to do so could be a little more time than the control you can like rely on the control to interact half a little less like tiring positions of your hands something like that. The controller gives you a little more feedback on these for example things that that requires grip you can have the feedback with the trigger so you put the trigger and you can know you are touching something and if you pair that with visual cue, you can feel it and you can feel in control, with only the Leap Motion the problem is that the pinch movement you can like see the pinch and try to do the pinch maybe know that something is happening but that's like a little microsecond that we're not sure really doing it well, it can get a little tiring and we need over an over that It can be a little stressing or tiring, so the leap motion would need some more type of feedback or guideline of feedback or something to compliment that lack of physicality and be very very very worth or try to find some way of having your hand free but still giving feedback that would be quite a challenge.	Feel weightless and hands are tight with Leap motion Uncertainty Feel comfortable with mixed interaction Two hands using Leap Motion can be tiring. Mixed interaction is comfortable Visual cue Not sure, stress or tired with Leap Motion Require feecback Improvement

Q6: What sort of use cases can you see as benefiting from this type of mixed interaction?

Interview Transcript	Codes
User #01 Obviously simulator hands down as a very good use case for the fact that you're sitting and you've got a million buttons that you could potentially touch I think something like PC building simulator pro where you pull components out if you had the ability to actually grab it with your hand and yank it out of the PC and do those sorts of	

procedures you could really train somebody to build a computer without having the fear that they would blow up your room. I think that I would probably like to try "Beat Saber" with it you know because the controllers they had this problem when you hit all the buttons whereas if you could just simply even if you held sticks and you could use these sticks as the Sabre that would be quite cool and being such a popular game and something this simple would be quite neat to see. Also, just not to having the controller, it's infuriating when you gotta use your VR setup in the controllers are flat and then you have to wait 15, 20 or an hour by then you're like I'll just play something else. So not having controllers as a huge convenience to not having to charge them, the complexity of having controllers in menus might be a bit of an issue like how do you get up a control menu without controller home button but maybe that could be circumvented by say clapping like repetitive way or voice to bring up the menu. I think that maybe they could actually be I was going to say first person shooters is probably not an ideal scenario for this type of control. I think there's a huge market for like you've got obviously the VR systems that are seat up commercially and people go and pay and just have a random game of VR in a little box or what not but also the same time the models of the guns could be specific to the weapon and that you're using at the time but there's a problem where you get too detailed and what you're holding and it doesn't become easy to put the gun away to change it out for another one or like weapon changing yeah and then if you go from a pistol it's simple because the controller mimics the handgrip so it's a very one to one motion, this would be perfect for people that have a single controller and like you say yeah and then that have the leap motion on the reload. So what happens in first person shooters if you bring your second controller up and you'll have to hold the grip and pull the slide back but you commonly smash the two controllers together because that too close where is it having emotion control it just doing the action above your controller would be a lot less problematic for the controller health, yeah and mag changes as well as you come up you can actually put the mag with the controller, when you're holding it, it doesn't relate to your actual hand it relates to the controller so it's like 100 mills above where you're actually supposed to be holding it so when you can fit it into the gun if it's not correct either they make it fake where it just magnetises into gun or it'll hit the side of the gun and flip around in your hand while you try to chunk them in. Some games are kind of bypass those issues by having mechanic steps use don't use magazines you know you have I think project Alex is a very good example that sort of system and of course if you want to real life military simulated you have to have magazines if you're going to World War Two you can't just magically make things happen yeah so I think there's ways around it and I think it's huge that will be hugely beneficial for certain types of games probably puzzle games too, where instead of having to have the controllers you can slide things around and connect wisely.	Charging controller is inconvinient Suggestion on FPS Suggestion on puzzle games

User #02 I think maybe in the medical field I think personally, something let's say surgery, if you have the left hand for like surgical scissors like physical objects that you hold right in the right hand for like moving stuff around the patient and like picking objects up I think it would be quite nice having like that coz I think this already surgery kind of VR games out there both controllers and a lot of doing surgeries finicky stuff of fingers right it also stuff of objects so it's kinda good to being able to do both, having mixed of interactions.	Suggestion on medical field
User #03 You know the game Boneworks? yeah so that was I played that on my vive and that's one of those games that had you used the bottom grip to hold onto things so I would have to take like kind of intermittent breaks to rest my hands cause I felt like there was a bit strain on it but and going on that's like a game that's really like physics based and you do a lot of those like fine movements with the controller but I notice that when you try to put something close together the controllers will hit each other like they crash into each other and you can't get closer than opposite the controllers in physical space as if it was my hands you could get a lot closer and you could probably do more fine adjustments it could be anything along those lines but I think there's a lot of stuff you could do with it I just can't think of anything. There's always those VR surgery things you did it in real time kind of things or anything that's like requires fine motor control it like but done from a super far distance. That's all I could think of. I really enjoy the project.	Suggestions on Boneworks The user experience is enjoyable
User #04 If I was speaking from like a gamer that a fantasy like sort of magic thing would be really cool but I'm thinking just like maybe even like a like a surgery SIM you've got that all in one hand and you've got like more precision stuff with your left hand, stuff like that like just being able to do more precise like a little pinch and pull rather than grabbing the entire thing in just being a way I think it be really interesting having that delicate precise motion with your fingers to do that sort of stuff and then having your left hand just ready on some sort of tool to handle like a little scalpel and just doing a cut I think something like that yeah in one hand have your free hand doing more precise motions so like surgery is like the first thing that comes to mind but more like mechanical stuff like teaching people how to use certain things even like cooking like having like the whole like from one hand having like the left doing the cutting would be really cool to have like that sort of stuff like just day to day SIM just job SIM and just it definitely opens up a really cool way to handle just a lot of things you can do in a game in terms of just how to play interactive thing. I was thinking about like a magic fantasy base like you have a sword in one hand and you have like your right hand doing spells like doing little finger motions to do the magic oh like doing your finger movements because like in a movie or whatever it's just like all I'm	Suggestion on magic fantasy-based types of game Finger motion Mechanical simulation New way to play interaction applications Magic fantasy application

going to make a circle with my hand do all these intricate things and then fireball comes out that kind of stuff. It will be really cool.	
User #05 I feel the interaction I have done on this flight simulator was significant because the joystick felt like I was actually using the joystick and the buttons were you know push buttons turning dials is what you do with your plan anyway so it feels more natural than to use like the control like a fist, kind of try to punch grab something or enjoy to punch a button it feels almost right.	This VR cockpit training study is significant Use controller on sidestick and Leap Motion on buttons are just right.
I feel like the easiest one I can think about would be something like "among us", it was a very popular game where you have cremates that that run around trying to do tasks because I only think about this is because in this game you are forced to do many sort of mini interactions, many mini games but in the actual gaming use your mouse so for example there be missions where you need to swipe a card so I feel like in vr you can just pick up the card with your hand and try to swipe it emotion wise because you can pinch pick up cards like I feel like that would be very fun and very useful than trying to grab the controller because you know you got me a card if you got controller feels much more earthy than a card right and then there will be things like trying to connect wires together which are very details, only use fingers where I just want to grab wires and put them together kind of connected wires and what other things.... simple almost mini game kind of aspects I feel benefit the most, I feel like many detail thing, for example like a flashlight with one hand for the controller actually you feel you're grabbing it, turn it on with finger grab and then you can do something intricate with your other hand ...that could be mixed I feel.	Suggestion on simple mini games
User #06 Truck simulator so I don't know maybe like when you're controlling like driving games as well like in controlling the stick shift and all that stuff because I always drive with just one hand that's a thing. I mean the only games that come into mine are like yeah simulation games but like shooting simulator games....just like having the controller too ah actually yeah the mixed one would work, say if you want to reload a gun in a fps shooter game, that'll be a really cool feature to be able to if you say if you're holding like a bold actions sniper rifle, that you can display manually like grasp on the bolt and then like eject the bullet I mean like in the shooting game but yet so the rifle you manually load the thing in with the with the leap motion and then you still have the controller then like holding the gun.	Suggestion on shooting simulator games
User #07 You know how like you grabbed onto something it's got some benefit because you can actually like for instance how you had the likes set the horizon is really easy coz you had a controller and you had like you're in control of like the rotational values in everything and sitting it there and with the hand you could use your fingers to do different like task like wanting to do an index to push button or to turn it or when you grabbing like that the handles you could like cross your	Seeing potential on mixed interaction

hand over it and position it closer so I feel like mixed interaction could like have some good potential with it..like different tasks like how you had the flying simulator you have like a like a joystick in front of you and you're using that to like turn the plane. I mean like for instance that would be quite good with simulation is like flying planes driving cars like if you were to drive a car you could use a controller to do the stick and other hand just turning the wheel. You could probably use it to be the gear and breaks. You could use it for they have to be quiet interactive games and for it to be mixed you'd have to have one right all the left side having like the need to use your fingers and the other one the need to like grab onto a joystick or something for that sort of mixed interaction to rank or make sense like for instance like if you were to have a blade and one those controller would be quite useful as you're actually feeling like you're holding something or if you like typing like something in that key code, you can use your fingers to like press the different keys in and something.	Suggestion on driving car sim
User #08 I can see a lot of training and I have already seen quite a couple of applications and training of heavy machinery or complicated machinery in general in which very interesting because you don't need to the big machine or do they need the actual space to train and you can be training quite well you have a one-on-one interaction with what you are supposed to learn and you can train perfectly well which is completely transferable your abilities from the virtual world to the real world. The other thing that the plus with these things is that you can train way more scenarios like for example that what to do if your plane is falling or out of control, in a real plane you cannot do that because you don't mean you have to crash your plane with you inside so you can actually train how to react how to do something in any scenario that is very difficult to do in real life, how to use the machinery in a dangerous scenario or in a scenario mean don't mean like danger for yourself or for other people	Suggestions on surgery training centre
With that new interaction mode in particular, the most interesting thing about the hand is that everyone knows how to use the hand, how to automatically think of different interactions like a pinching the grabbing the pulling. Anything that requires you to do something else with your hand yes leap motion especially but maybe later technologies are quite good in reconstructing and giving a good track of your hand so if you need something that requires finesse for it, nice because they are not delaying, delegating the direction to the controller and what the controller can do, how many buttons you can actually use your hand and everyone knows how to use this so it's a good is a good way of using technology for people that are not across that technology to do more kinds of interaction. I quite like your finger or pinching or a more little precision like fitness movement like surgery centre for example that would be interesting	Mixed interaction is a good way for people to do different interactions Surgical

because you can do that with more technology like the purpose scenarios like fitness is necessities is what you want more precise interaction , typing for example of things that require you like moving I don't know yeah I know like piano like something like not only the BLOB of your hand but the fingers or finessing or moving that will be interesting.	